AN ABSTRACT OF THE THESIS OF

Peter J. Raschio for the degree of Master of Science in Electrical Engineering presented on July 19, 1994.

Title: Evaluation of Dynamically Controlled Resistive Braking for the Pacific Northwest Power System

Redacted for Privacy

Abstract approved: ______________

Dr. René Spée

Today's power systems are undergoing dynamic changes in their operation. The high cost of capital improvements that include new generation and transmission projects has prompted power system planners to look for other alternatives in dealing with increased loads and overall system growth. A dynamic braking resistor is a device that allows for an increased rating of a transmission system's transient stability limit. This allows increased power flows over existing transmission lines without the need to build additional transmission facilities.

This thesis investigates the application of dynamically controlled resistive braking in the Pacific Northwest power system. Specifically, possible control alternatives, to replace the present dynamic brake control system at Chief Joseph station, are examined. This examination includes determination of appropriate locations for control system input, development of control algorithms, development of computer and laboratory power system models, and testing and recommendations based upon the developed control algorithms.

Evaluation of Dynamically Controlled Resistive Braking for the Pacific Northwest Power System

by

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A THESIS

submitted to

Oregon State University

in partial fulfillment of

the requirements for the

degree of

Master of Science

Completed July 19, 1994

Commencement June 1995

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Date thesis is presented July 19, 1994

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CHAPTER 1 INTRODUCTION

1.1. Flexible AC Transmission

Today's power systems are undergoing dynamic changes in their operation. In the Pacific Northwest environmental concerns, such as the possible listing of the Columbia river salmon on the endangered species list, compounded with low water years has reduced generation on the Columbia and Snake river hydro-systems. The high cost of capital improvements that include new generation and transmission projects has prompted power system planners to look for other alternatives in dealing with increased loads and overall system growth. One solution is the use of power electronics in power system applications in FACTS (Flexible AC Transmission) Devices. These devices can provide fast reliable control for responding to stability problems, and hence increase a transmission line's stability limit. They also allow for the control of power flow in a transmission system. Their use allows the power system operator to fully utilize transmission resources. One possible FACTS device is the thyristor switched dynamic brake. This device can support transient stability in a power system and provide for system damping. Current thyristor technology allows the construction of thyristor valves capable of switching thousands of watts. [1,4]

1.2. Western Power System Overview

The Bonneville Power Administration (BPA) operates the major transmission system in the Pacific Northwest (NW). A large concentration of hydroelectric power exists in the Columbia river basin. A strong 500 kV grid connects Columbia river generation to Northwest load centers in Western Washington and Oregon. A large source of combination coal and hydro power generation exists in Idaho and Montana. Two parallel 500 kV transmission lines couple this generation to the load centers west of the Cascades. Three 500 kV AC transmission lines and a 1000 kV DC Transmission line strongly couple the Northwest and California power systems. Total transmission capacity between the NW and California is currently 7900 MW. (See Figure F.1 in Appendix F) [3]

1.3. Existing Brake Controller at Chief Joseph

BPA installed a braking resistor at Chief Joseph Substation in the early 1970's. This device is switched by a vacuum circuit breaker onto the 230 kV substation bus and is capable of dissipating 1400 MW. During a major system fault generation in the Pacific Northwest quickly accelerates. BPA installed the brake to dissipate this accelerating power during the first swing of the fault and hence reduce the severity of the tie-line swing between the NW and California. This transient stability control measure allowed for increased transmission capacity along the Intertie lines with California. [3]

The current resistive brake control system consists of power rate relays located at Chief Joseph and John Day, measuring accelerating power. If the measured accelerating power exceeds a preset accelerating power level and the generator bus voltage drops, the relay sends a close signal to the brake controller. The brake controller inserts the brake for a fixed time of 30 cycles and only for the first swing of a transient disturbance. [3]

1.4. Thesis Goals

The control system for the Chief Joseph Dynamic Brake was designed over twenty years ago. The need to replace the current brake control relays gives an opportunity to investigate the operation of the entire control scheme and look at possibilities to improve it. This thesis investigates possible control alternatives to replace the present system. Specific tasks include:

1. A study to investigate the optimal number and location of control system inputs in the Northwest power system. (Chapter 4)
2. Investigation of improved control algorithm for three phase breaker switched dynamic braking. (Chapter 3 and 5)
3. Investigation of single phase breaker switched dynamic braking. (Chapter 3 and 5)
4. Preliminary design and analysis of a thyristor switched dynamic brake. (Chapter 3 and 5)
5. Develop and test a single machine infinite bus laboratory model. (Chapter 6)
6. A final comparison of three phase breaker, single phase breaker and thyristor switched dynamic braking. This includes a comparison of operation advantages and disadvantages as well as a preliminary cost analysis. (Chapter 7)

BPA will use the research outlined in this thesis in the design of a new control system for the Chief Joseph dynamic brake.

1.5. Project Resources

To meet the project goals EMTP (electro-magnetic transients program) models and a single machine infinite bus laboratory power system model are developed. The EMTP models include two 5-generator models, one for a light and one for a heavy loading condition. These models consist of simple transmission line models, and incorporate no other dynamic control such as governors, power system stabilizers or automatic voltage regulators. Hence there is minimal inherent system damping. Despite these simplifications the models do provide understanding of the main area interactions in the Western Power System and allow the observation of Chief Joseph dynamic braking effect on area interactions. Results from these models are representative of the system for first swing analysis. Chapter 5 and Appendix A contain fuller detail of these models.

The single machine infinite bus (SMIB) laboratory model is derived from a portion of the five generator western power system model, which represents the transmission of power from the Northwest to California. An equivalent generator represents the Northwest system and an infinite bus represents California. To use these parameters in a laboratory model an appropriate base value for voltage and apparent power is selected. As a result, a 3.5 kW dynamic brake is connected to the "Northwest" equivalent bus, which is represented by a 10 kVA, 4 pole synchronous generator. This model is explained in more detail in Chapter 6, and Appendix B.

CHAPTER 2 GOVERNING SYSTEM EQUATIONS

2.1. System Equation Derivation (SMIB Model)

Power system control is inherently a difficult problem. To control a system it is necessary to have adequate models. In the case of power systems, these models must include non-linear loads, hundreds to thousands of busses, high order models of synchronous machines, interconnection to neighboring systems, and complex existing control systems. The resulting problem representation has innumerable inputs, complex and unclear interaction among thousands of variables, and is nonlinear in nature. For these reasons most investigations in power system control rely on the use of simple equivalents, such as the single machine infinite bus power system model illustrated in fig. 2.1.

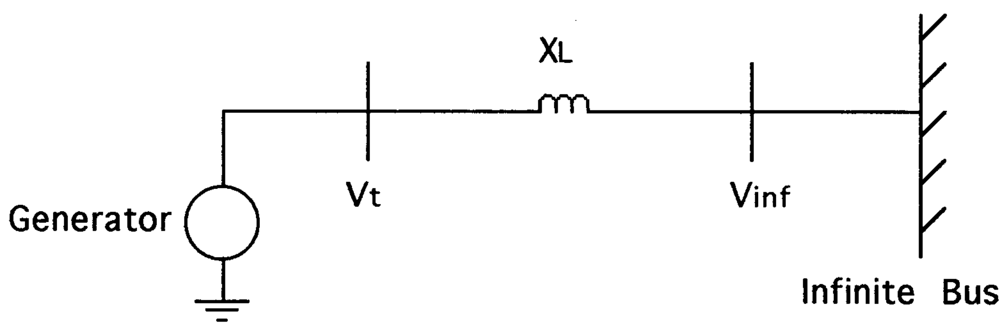

Figure 2.1 Single Machine Infinite Bus System

The differential state equations that follow describe the connection between the mechanical and electrical system of this network as expressed in equation 2.1. This equation is the foundation for power system transient stability analysis. During steady-state operation of the system, the mechanical (P_{mech}) and electrical power (P_{elec}) are equal, hence the system is at an operating point at which the swing angle δ is constant and the swing angle acceleration is zero. During a system disturbance, such as a transmission line fault, Pm which is a function of the system network, will change quickly, while mechanical power from the prime mover cannot not change in less than a few seconds. The electrical power and the mechanical power do not equal each other. The difference in power accelerates the generator mechanical system inertia, hence the generator swing angle acceleration is now greater then zero. If the new swing angle that again equates mechanical and electrical power is a stable operating point, the system will oscillate about δ with decaying oscillations due to system damping. [5]

$$\frac{2H}{\omega_r}\ddot{\delta} = P_{mech} - P_m \cdot \sin(\delta)$$

$$P_{elec} = P_m \cdot \sin(\delta) \tag{2.1}$$

For investigating system response for the first swing of a power system disturbance (first few seconds) it is usually adequate to use the classical generator model. This model is composed of a constant voltage source behind a transient reactance illustrated in fig. 2.2. The constant voltage corresponds to flux linking the main field winding. During a transient disturbance this flux remains relatively constant for a second or longer due to induced currents in the rotor circuit resulting from changes in current in the armature circuit. The combination of excitation systems and the armature current reaction helps maintain constant flux linkage for a few seconds. [5]

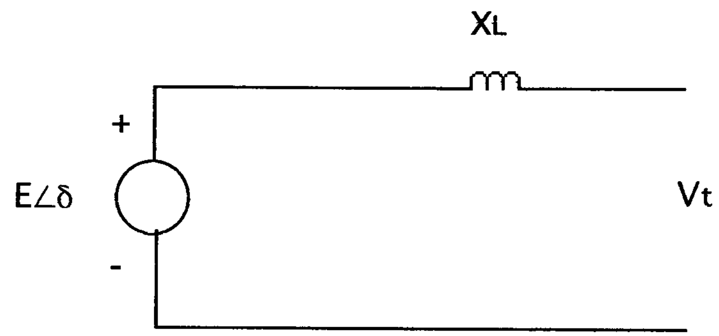

Figure 2.2 Representation of Synchronous Machine in Classical Model

Using the classical generator model in a single machine infinite bus system allows for the study of first swing system dynamics using a simple 2nd order system expressed in equation 2.2. Additional assumptions built into this model include constant mechanical input power during the transient period of interest, negligible representation of system damping, and correlation of mechanical generator rotor angle and electrical phase angle. Notice this model is also simplified with purely inductive transmission line models and the absence of any local loads. [5]

$$\dot{\delta} = \omega$$
$$\dot{\omega} = \frac{\omega_o}{2H} \cdot P_{mech} - \frac{\omega_o}{2H} \cdot \frac{E' \cdot V_{\inf}}{(X_L + X'_d)} \cdot \sin(\delta) \tag{2.2}$$

2.2. Condition for Stability

The developed system model is now used to investigate the stability limits of the power system. The parameters for this system model are derived from the light spring 5-generator EMTP model described in Chapter 5. The generator in the model represents the Northwest equivalent generator. The transmission lines represent the

AC Intertie between the Northwest and California. The infinite bus voltage is the voltage at the Northern California generator bus. During steady-state power system operation, for a mechanical power input to the generator of P_{mech}, the generator rotor angle is δ_1. In this example the single transmission line in the SMIB classical model is replaced with two parallel transmission lines. A fault occurs on one of the transmission lines. Figure 3.3 shows the power angle curves for this network configuration. The per unit power transfer level is based on the power transfer between the Northwest and Northern California in the 5-generator light spring EMTP model. The generator rotor angle will swing as the system tries to balance the mechanical and the electrical power. Applying the equal-area criterion allows the determination of stability of the system without solving the swing equation. Figure 2.3 illustrates that the maximum power that the faulted network can transfer is less than the mechanical power driving the generator. This indicates that the system will go unstable if relays do not quickly trip circuit breakers to clear the fault. There is a critical angle δ_c for which circuit breakers must clear the faulted system to maintain stability. This critical angle corresponds to a critical clearing time, t_{cr}. If fast relaying quickly opens the faulted transmission line, isolating the fault in less than t_{cr} the system is stable. The cleared network has a power angle swing that allows a new operating point δ_2. [7]

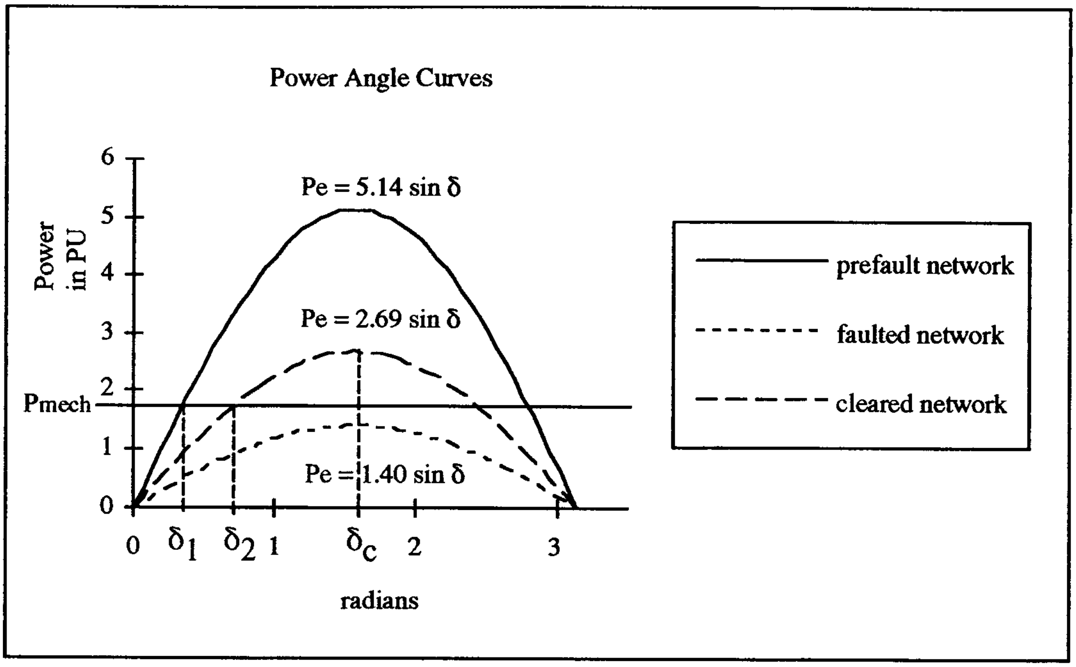

Figure 2.3 Plot of Power Angle Curves

The transient stability of a transmission line network places a limit on the amount of power a transmission line can transfer. Inserting the dynamic braking resistor during a fault condition places a load directly at the generator bus. This in essence reduces the value of the accelerating mechanical power during brake application since a portion of the generator power will go directly to the braking resistor, thus reducing the power that the transmission lines must transfer. Reducing P_{mech} will increase the critical clearing angle δ_c, and the critical clearing time t_{cr}. The use of the dynamic braking resistor increases the limit on power transfer over a transmission line while maintaining stability.

2.3. Equations with Braking Resistor

The placing of a braking resistor at the generator bus of our SMIB model adds some complexity to the equations as expressed in equation 2.3.

$$P_{elec} = \frac{(X'_d + X_L)E' \cdot V_{\inf} \sin\delta + \frac{1}{R}(X'_d \cdot X_L \cdot E' \cdot V_{\inf} \cos\delta + X_L^2 \cdot E'^2)}{\frac{X'_d \cdot X_L^2}{R^2} + (X'_d + X_L)^2} \tag{2.3}$$

It is more convenient to model the braking resistor as a fixed load independent of generator bus voltage or generator rotor angle. This simplification allows for easier stability analysis of the system including the dynamic brake as expressed in equation 2.4. [2]

$$\begin{aligned} \dot{\delta} &= \omega \\ \dot{\omega} &= \frac{\omega_o}{2H} \cdot P_{mech} - \frac{\omega_o}{2H} \cdot P_{brake} - \frac{\omega_o}{2H} \cdot \frac{E' \cdot V_{\inf}}{(X_L + X'_d)} \cdot \sin(\delta) \end{aligned} \tag{2.4}$$

2.4. Phase-Plane Analysis

Analyzing the phase portraits of the second order system with and without the braking resistor gives a different perspective of the transient response of our SMIB classical model. This analysis allows for the prediction of system stability and the investigation of the effect dynamic braking has on increasing transient stability of the system. Figure 2.4 shows a phase plane plot of the previous power system model for the pre-fault, post-fault, and post-fault with braking resistor conditions. The initial conditions and the transient conditions are the same as those placed on the system investigated in the previous section. Before the system disturbance the pre-faulted system has a stability limit defined by the separatrix illustrated in fig. 2.4. When a fault occurs the generator rotor angle accelerates as the machine swings toward instability. Circuit breaker operation must clear the transmission line before the trajectory reaches the post-fault separatrix. Even with this operation, the system may still go unstable if the rotor acceleration is continuing to increase after circuit breaker operation. The use of a braking resistor is investigated to determine its effects on system stability. A 1400 MW braking resistor is used to represent the current Northwest power system braking provided by the actual Chief Joseph dynamic brake. Figure 2.4 illustrates how the addition of the braking resistor pushes the separatrix and the stability limit to that of the original pre-fault system. This validates the stability analysis using power angle curves that showed that using the braking resistor allowed the transmission of increased power in a transmission line due to the increased transient stability limit of that line. [6,8]

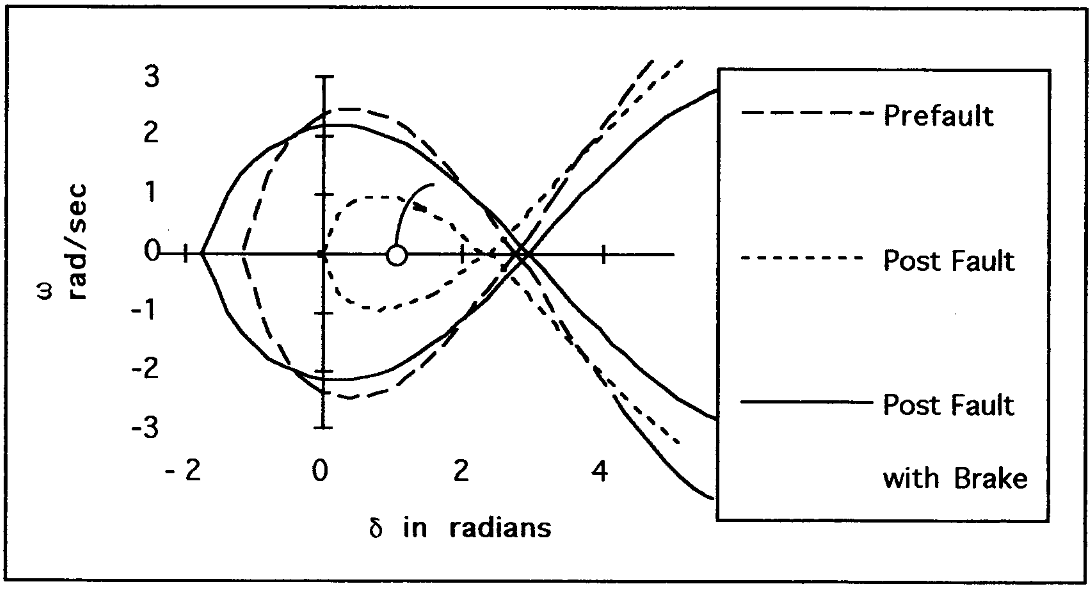

Figure 2.4 Phase Plane Plot of SMIB Model Dynamics

CHAPTER 3 CONTROL ALGORITHMS

3.1. Introduction

Since the initial design and construction of the Chief Joseph dynamic brake over twenty years ago BPA engineers have presented several ideas for improvements to the brake control system. Initial brake control designs suggested that future control schemes address use of the brake for second swing stability. Other suggestions include inserting the brake based on a ratio of change in power to generating power, inserting the brake if the total energy of acceleration during a swing exceeds some predetermined amount and inserting the brake for over-frequency due to load-shedding. This investigation of possible control algorithms uses the twenty years of operating experience of the current dynamic brake system.

Depending upon the switching method used with the brake there are limitations on control parameters for the brake. The current system uses vacuum circuit breakers to switch all three phase of the brake simultaneously. The only control freedom with this switching are the turn-on and turn-off times of the brake. The brake power output is a constant 1400 MW. Another switching option being investigated is switching of individual phases of the braking resistor. This method gives more freedom for control by allowing the power dissipation in the brake to be adjusted in 467 MW steps. The final switching option being investigated is the use of thyristors to switch the brake. This power electronic option allows complete control of the brake power dissipation from 0 to 1400 MW.

In developing these control algorithms a group of fault studies is simulated using the two 5-generator EMTP models. These models are described in detail in chapter 5 and appendix A. Six different disturbances are investigated using each model. For each of these faults the simulation applies the brake for 0 to 30 cycles in steps of 5 cycles. These studies provide a basis for developing the control algorithms that follow. (See Appendix E)

3.2. Brake Turn-On Control

The first control decision a controller must make is when a power system disturbance requires dynamic braking action to maintain transient stability. The current power rate relay measures accelerating power and switches in the brake if the relay input exceeds a preset accelerating power level. [3] The original purpose of the brake was to slow the Northwest power system for faults that interrupted power transfer with California. Therefore a good control input location would be one that represents the average Northwest power system response to system disturbances. A possible input to control turn-on of the brake is to look at the relative velocity of a generator. The controller can approximate relative velocity by integrating accelerating power (P_a) as expressed in Equation 3.1, where ω_0 is the steady state electrical frequency and H is the generator inertia constant. The relative velocity of a generator directly relates to the energy stored in the inertia of the generator. A controller can insert the brake if the relative velocity exceeds a fixed level due to a system disturbance. This, in essence, leads to brake insertion if the total energy of acceleration during a swing exceeds a fixed level.

$$\omega = \int \frac{\omega_o}{2H} \cdot P_a \tag{3.1}$$

3.3. Brake Turn-Off Control

In energy terms the brake is best used if the amount of energy absorbed in the brake is close to the amount of energy that accelerates the Northwest generators. The fault studies with the 5-generator model (discussed in Chapter 5) show that there is a practical limit to the time length a controller can apply the brake. An extended insertion of the braking resistor will separate the Chief Joseph generators form the rest of the power system. This condition will cause more harm to the Northwest system than the benefits from dynamic braking. Observing the relative velocity at the Chief Joseph generator for several faults shows that a turn-off level of -0.7 to -1.0 rad/sec produced the best reduction of first swing velocity at the Northwest equivalent generator. This is illustrated with an AC Intertie fault in fig. 3.1.

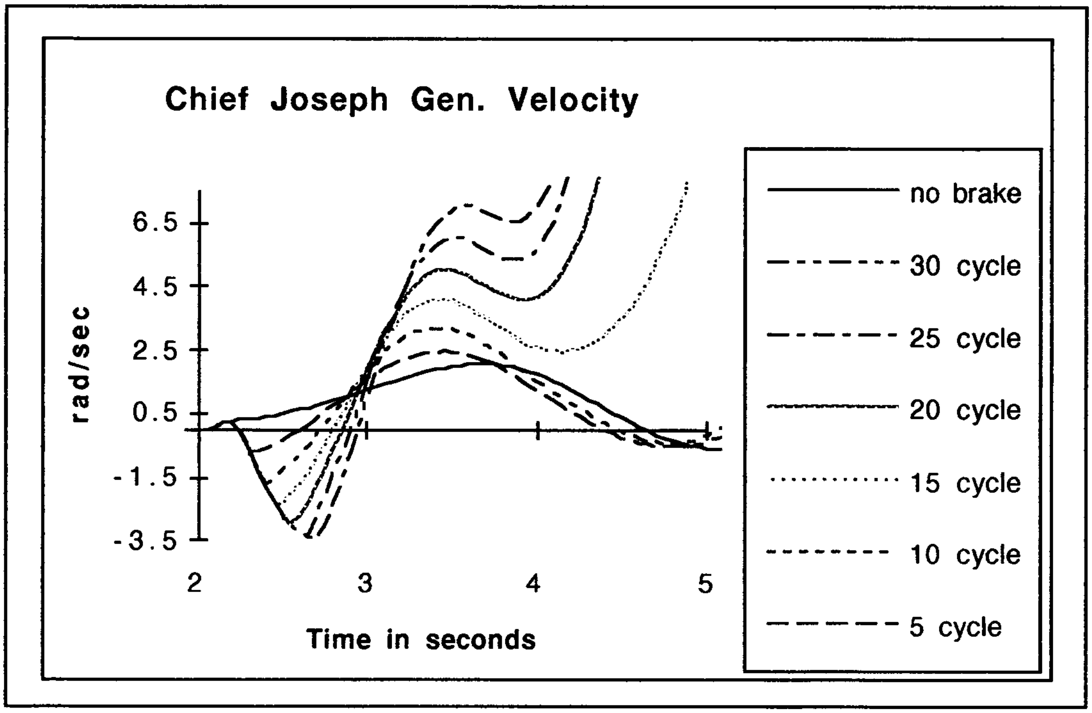

Figure 3.1 John Day-Northern California AC Intertie Fault on the Light Spring Model, Chief Joseph Generator Velocity

Turn-off control of the dynamic brake allows for braking of smaller power system disturbances. Previous transient stability simulation by BPA engineers shows that dynamic braking is more effective the sooner a controller energizes the brake after a fault occurs. Turn-off control allows a decrease in the turn-on relative velocity level of the brake. If a fault that requires minimal braking causes the controller to turn on the brake, the relative velocity level for turn-off at Chief Joseph is reached quickly. The only limitation is with the switching device. If a circuit breaker switches the brake there is a time delay associated with this switching. The brake is most effective for faults that require at least the minimum braking duration possible with the available switching device.

3.4. Multiple Brake Applications

The limitation on the duration of brake application, imposed to prevent Chief Joseph generator separation, may make necessary multiple brake insertions for some severe disturbances. Succeeding brake insertions would be of reduced time duration due to the reduced stored energy in the Northwest generator's inertia. If the dynamic braking system uses either single phase breaker or thyristor switching, then second or third brake insertion can be of reduced braking power from the first. This may allow for the more rapid damping of oscillations from these system disturbances.

3.5. Exponential Decrease in Brake Power

Switching of a fixed amount of brake power onto the power system is in effect introducing a step power disturbance. Switching off the brake introduces another step power disturbance. Prior research involving variable structure control of dynamic brakes shows that for best performance braking power should exponentially decrease during brake application. [2] The time constant associated with this decrease should approximate that of the transient disturbance. This is not possible with three phase breaker switching which dissipates a fixed 1400 MW when the brake is applied. A discrete approximation of this exponential decay is possible with single phase breaker switching. Thyristor switching allows for a continuous exponential decrease of power.

3.6. Initial Brake Power

Another aspect of flexibility in the use of either single phase breaker or thyristor brake switching is the ability to vary the initial brake power when the controller detects a system disturbance. Studies implementing single phase switching, where application of the brake is at reduced power levels, show a better performance for some faults. This is compared with studies using three phase switching that applies the full brake power, as illustrated in figs. 3.2 and 3.3. For a specific fault, three phase breaker switching of the brake reduces the peak relative velocity of the Northwest equivalent generator for the first swing from 1.4 rad/sec to 1.0 rad/sec. Reduced brake power obtained with single phase breaker switching of the brake allows a further reduction of the peak relative velocity to 0.9 rad/sec. This is a 25% improvement over the full brake power response.

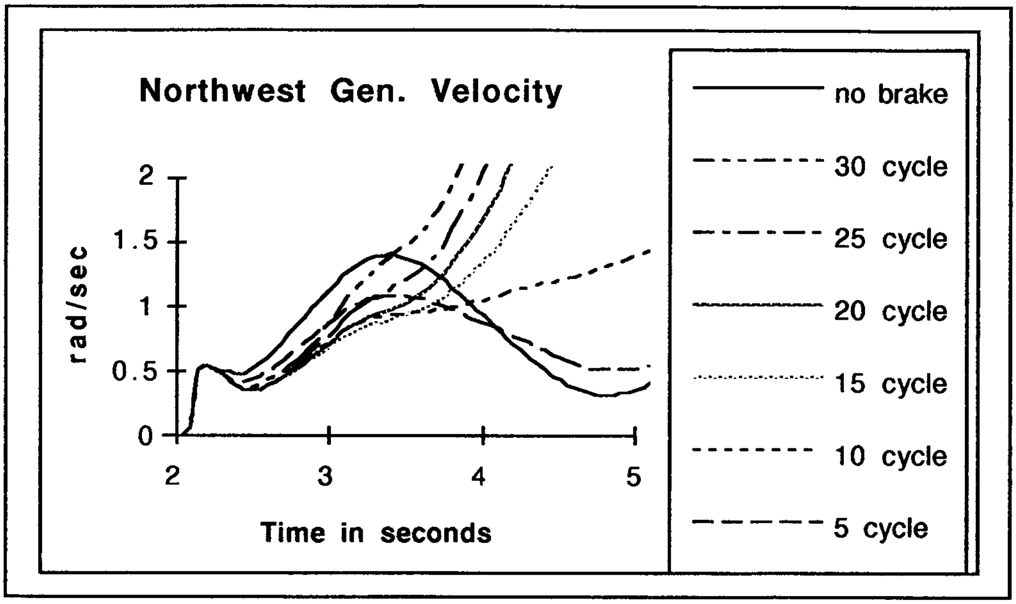

Figure 3.2 John Day-Southern California 3rd AC Intertie Fault with 3ø Circuit Breaker Switched Braking

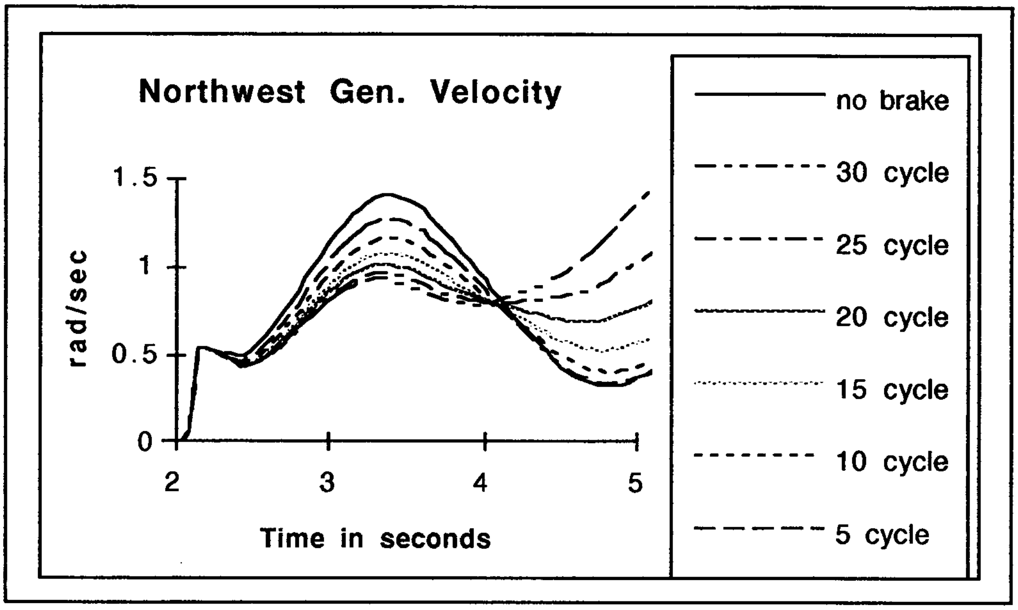

Figure 3.3 John Day-Southern California 3rd AC Intertie Fault with 1ø Circuit Breaker Switched Braking

The average Northwest accelerating power provides a good measure of the severity of a power system disturbance. Measuring the accelerating power at the moment the brake controller indicates a brake application can be a valuable input to calculate the necessary initial brake application power.

CHAPTER 4 EVALUATION OF CONTROL INPUT LOCATION

4.1. Introduction

The objective of this area of research is to determine the necessary power system inputs and their location for dynamic brake control. Currently BPA uses power change detector relays at Chief Joseph and John Day to measure a disturbance. The present research builds on the existing brake and control system structure. Using a detailed transient stability program model of the Northwest power system, BPA provided generator voltage and maximum accelerating power for 49 different three phase faults. (See Tables 4.1, 4.3) The sensitivity of the current brake controller input sites and the need for new or additional input locations is investigated using these stability studies. Additionally, the feasibility of an analytical approach is investigated, in which individual machine acceleration to the area center of inertia is used in the determination of the required number of measurements.

4.2. Transient Stability Studies

To facilitate an analytical approach, in determining optimal input location and number, BPA engineers provided numerous transient stability computer simulation studies of the Western power system. These studies are reflective of two seasonal conditions, the heavy spring run off, which entails heavy generation, and the light summer and autumn, which involves light generation levels. Each study provides the maximum accelerating power for essentially every generator group in the Northwest power system for both loading conditions. Table 4.1 lists the generator groups provided in the transient stability studies with their group inertia in electrical megawatt seconds (EMWS). Balanced three phase line to ground faults are investigated in these stability studies. Table 4.2 lists the observed transmission line faults. Appendix C provides a detailed list of all generator accelerating powers determined for each fault.

Heavy Spring						Light Autumn		
Generator	kV	EMWS	Generator	kV	EMWS	Generator	kV	EMWS
BONN PH2	13.8	1456	ICE H3-4	13.8	371	ASHE 2	25.0	4443
BONNVIL1	13.8	927	ICE H5-6	13.8	742	BOARD F	24.0	1518
BONNVIL2	13.8	1530	JOHN DAY	13.8	7856	BONN PH2	13.8	1456
BOUNDARY	14.4	962	LIBBY	13.8	2680	CENTR G1	20.0	2204
BOUNDRY2	14.4	962	LIT GOOS	13.8	2946	CENTR G2	20.0	2204
BOYLE	11.5	223	LOW GRAN	13.8	2946	CHIEF J5	13.8	3263.7
CAB GORG	13.8	190.8	LOW MON	13.8	2946	CHIEF JO	13.8	1808
CENTR G1	20.0	2204	MCNARY 1	13.8	702	COULEE 2	13.8	10314
CENTR G2	20.0	2204	MCNARY 2	13.8	2388	COULEE51	15.0	9132
CHIEF J2	13.8	1632	MCNARY 2	13.8	2388	DALLES 3	13.8	2072
CHIEF J5	13.8	3263.7	NOXON	14.4	1128	DIABLO	13.8	570.6
CHIEF JO	13.8	1808	NOXON 5	14.4	375.6	HUNGRY H	13.8	2096
COULEE 2	13.8	10314	PELTON	13.8	258.9	ICE H3-4	13.8	310
COULEE51	15.0	9132	PRIEST R	13.8	640	JOHN DAY	13.8	7856
COULEE52	15.0	7160	PRIESTR2	13.8	2560	LIBBY	13.8	2680
COULEE52	15.0	3580	ROCK IS2	6.9 1	951	LIT GOOS	13.8	2946
DALLES 1	13.8	1020	ROCKY RH	15.0	2366	LOW GRAN	13.8	2946
DALLES 3	13.8	2072	ROSS 42	13.8	1150	LOW MON	13.8	2946
DALLES21	13.8	1530	ROSS 44	13.8	1150	MCNARY 1	13.8	702
DALLES22	13.8	1020	ROUND BU	13.8	1536	MCNARY 2	13.8	2388
DIABLO	13.8	570.6	RRCH8-11	15.0	1536	NOXON 5	14.4	375.6
DWOR 3	13.8	786	TENASKA1	13.8	100*	PELTON	13.8	258.9
DWOR 1-2	13.8	616	TENASKA2	13.8	100*	PRIESTR2	13.8	2560
ENSERCH1	13.8	100*	TENASKA3	13.8	100*	ROCK IS2	6.9	951
ENSERCH2	13.8	100*	TEXWEST1	13.8	100*	ROCKY RH	15.0	2366
ENSERCH3	13.8	100*	TEXWEST2	13.8	100*	ROUND BU	13.8	1536
ENSERCH4	13.8	100*	TEXWEST3	13.8	100*	WANAPUM	13.8	1980
HUNGRY H	13.8	2096	TEXWEST4	13.8	100*	WELLS	14.4	2960
ICE H1-2	13.8	620	WANAPUM	13.8	1980			
ICE H3-4	13.8	310	WANAPUM2	13.8	660			
			WELLS	14.4	2690			

Table 4.1 Generators and their Inertia for Spring and Autumn Cases

Case	Fault	Case	Fault
1	GRIZZLY 500	50	MONROE 500 ECHOLAKE 500
7	ALVEY 500 DIXONVLE 500	51	OSTRNDER 500 PEARL 500
8	DIXONVLE 500 MERIDINP 500	52	TROUTDAL 500 OSTRNDER 500
10	MERIDINP 500 CAPTJACK 500	53	MCLOUGLN 500 OSTRNDER 500
11	CAPTJACK 500 MALIN 500 1	54	SCHULTZ 500 RAVER 500 2
13	SUMMER L 500 BURNS 500	55	VANTAGE 500 HANFORD 500
15	BURNS 500 MIDPOINT 500	56	HANFORD 500 VANTAGE 500
16	MIDPOINT 500 BURNS 500	57	ASHE 500 HANFORD 500
18	PONDROSA 500 SUMMER L 500 1	58	LOW MON 500 ASHE 500
20	MALIN 500 SUMMER L 500	59	LIT GOOS 500 LOW GRAN 500 2
23	OLINDA 500 CAPTJACK 500 1	60	LOW GRAN 500 LIT GOOS 500 2
24	ROUND MT 500 MALIN 500 1	61	HATWAI 500 LOW GRAN 500
28	MARION 500 ALVEY 500	62	DWORSHAK 500 HATWAI 500
30	PEARL 500 MARION 500	63	SACJWA T 500 LOW MON 500
34	KEELER 500 PEARL 500	64	MCNARY 500 SACJWA T 500
40	SANTIAM 500 MARION 500	65	TABLE MT 500 TESLA 500 1
41	ALLSTON 500 KEELER 500	66	VACA-DIX 500 TESLA 500 1
42	PAUL 500 ALLSTON 500 2	67	CUSTER W 500 MONROE 500 2
43	RAVER 500 PAUL 500	68	ING500 500 CUSTER W 500 2
44	SATSOP 500 PAUL 500	69	TAFT 500 DWORSHAK 500
45	OLYMPIA 500 PAUL 500	70	GARRISON 500 GARRISON 230
46	TACOMA 500 RAVER 500	71	HOT SPR 500 TAFT 500
47	COVINGTN 500 RAVER 500	72	BELL BPA 500 TAFT 500
48	MAPLE VL 500 ECHOLAKE 500 2	77	COULEE 500 COULEE 230
49	ECHOLAKE 500 RAVER 500		

Table 4.2 BPA System Faults in TSP Study

4.3. Faults Requiring Braking

BPA's 4800 MW AC Intertie remedial action scheme (RAS) requires braking to maintain power system stability following line loss conditions as listed in table 4.3. [9] There are other faults and line loss conditions which, while not requiring braking to maintain stability, could benefit from brake application to quickly dampen the transient disturbance. One way to determine these faults is to investigate the generator rotor angle acceleration at specific generation locations, and use this information to determine an average system rotor angle acceleration. This average acceleration can be used to determine qualitatively the amount of braking required for a disturbance.

Single Line Loss	2-Line Losses
Alvey-Dixonvolle	Grizzly-Captain Jack & Grizzly- Malin
Captain Jack-Meridian	Ashe-Hanford & Lower Monumental- Hanford
Dixonville-Meridian	Ashe-Marian #2 & Ashe-Slatt #1
Grizzly-Captain Jack	John Day-Big Eddy #1 & John Day Big Eddy #2
Grizzly-Malin	John Day-Grizzly #1 & Buckley-Grizzly
Grizzly-Summer Lake	John Day-Grizzly #2 & Buckley-Grizzly
Hanford-John Day	John Day-Grizzly #2 & Slatt-John Day
John Day-Grizzly #1	Slatt-Buckley & Ashe-Marion #2
John Day-Grizzly #2	Slatt-John Day & Slatt-Buckley
John Day- Marian	Ashe-Hanford & Lower Monumental-Ashe
Marion-Alvey	Ashe-Hanford & Hanford-John Day
Summer Lake-Malin	Ashe-Marion #2 & Marion-Alvey
Vantage-Hanford	Ashe-Marion #2 & McNary-Slatt
Captain Jack-Olinda	Ashe-Slatt #1 & McNary-Slatt
Malin-Round Mountain #1	John Day-Big Eddy #2 & John Day-Marion
Malin-Round Mountain #2	McNary-Slatt & Slatt-Buckley
Malin-Round Mtn & Malin PRR N-S	Slatt-John Day & McNary-Slatt
Captain Jack-Tracy & CPJK PRR N-S	

Table 4.3 BPA AC Intertie RAS Braking Requirements

4.4. Determination of Average System Response

Immediately following a power system disturbance, the generators of the power system share the impact of the disturbance according to the electrical proximity of each generator to the disturbance. This initial transient period has a very small time constant. Following this transient period the generators will share the impact of the disturbance as a function of their inertia. As the generator oscillation caused by this disturbance subsides, the system response will settle to the mean acceleration. Determining this average system response will provide information on the response of the overall power system to specific power system disturbance. Hence the severity of individual disturbances can be quantified. [5]

In determining an average system response, the rotor angle acceleration is calculated for an equivalent generator at each of the input sites where accelerating power is available. The individual generator accelerating power

$$P_a = \frac{(2 \cdot W_k \cdot \dot{\omega})}{\omega_e} \tag{4.1}$$

leads to a rotor angle acceleration

$$\dot{\omega}_i = \frac{(\omega_e \cdot P_{ai})}{(2 \cdot W_{ki})} \tag{4.2}$$

where

ωi:	Rotor angle velocity for the ith generator in rad/sec
Wki:	Generator inertia in EMWS
ωe:	Electrical frequency in rad/sec
Pai:	Accelerating Power in watts.

In obtaining the average system acceleration an inertial center is first defined as

$$\overline{\omega} = \frac{\sum_i (\omega_i \cdot W_{ki})}{\sum_i W_{ki}} \tag{4.3}$$

The average system acceleration is then calculated for both spring and autumn cases with the available accelerating power inputs from equation 4.4.

$$\overline{\omega} = \frac{\sum_i \frac{(\omega_e \cdot P_{ai})}{2}}{\sum_i W_{ki}} \tag{4.4}$$

Figure 4.1 shows rotor angle acceleration for the Heavy Spring cases and figure 4.2 shows the rotor angle acceleration for the Light Autumn cases. Standard deviation is also calculated using the maximum rotor angle acceleration for each generator, and is included in the figures as a band about the system average acceleration. Table 4.2 provides a cross-reference of the faulted transmission line names to a fault identification number used throughout this chapter. Since all major generation is used to obtain the system average it is believed that a system average accurately represents an equivalent Pacific Northwest generator response to each of the faults applied. These faults are representative of all major possible faults on the BPA 500 kV transmission system illustrated in appendix F.

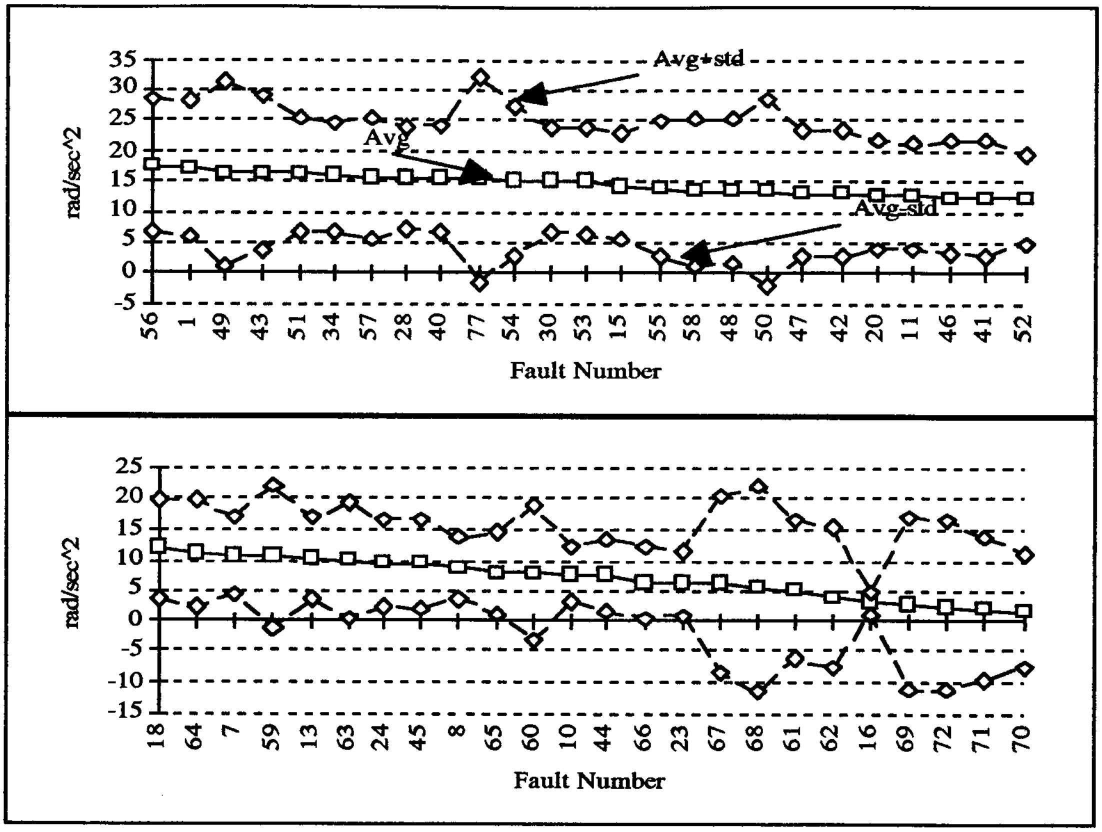

Figure 4.1 Heavy Spring Case Average Rotor Acceleration

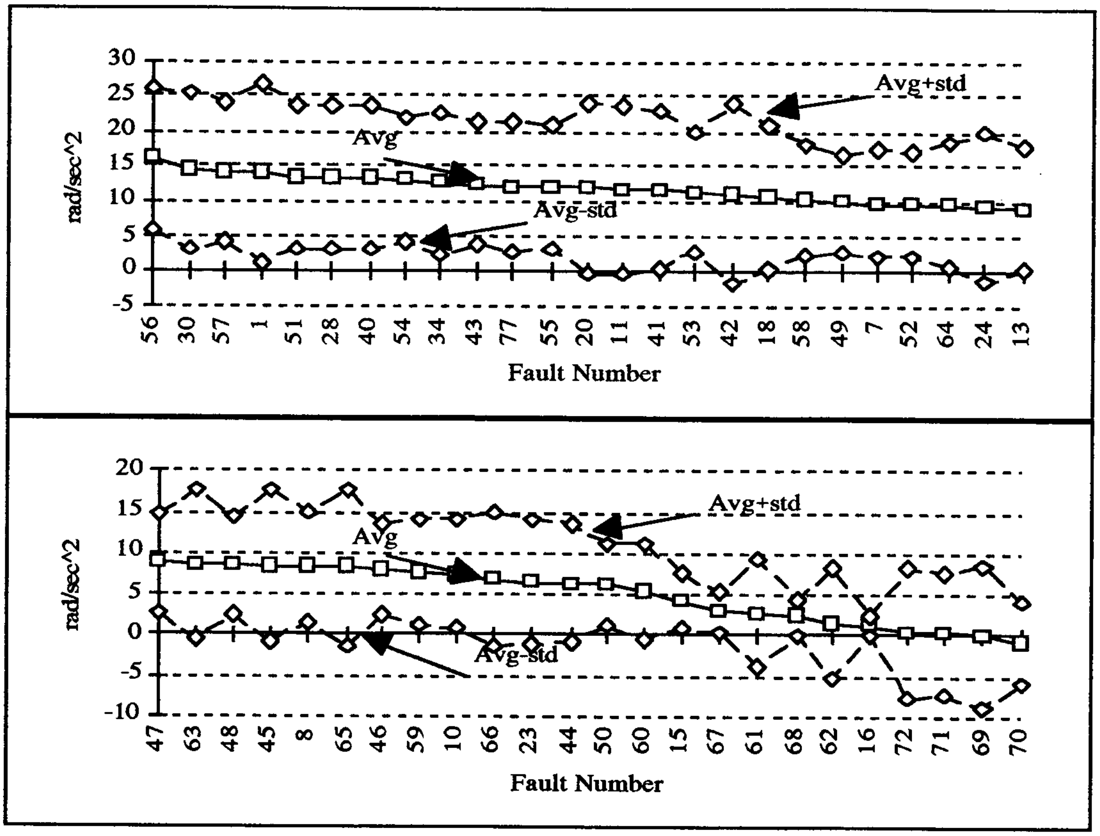

Figure 4.2 Light Autumn Case Average Rotor Acceleration

4.5. Input Site Observability

Once an average system acceleration is determined for each of the faults studied, this average is compared with the rotor angle acceleration determined at each generator site. Those generator groups that most closely follow the average system acceleration should provide the best input site locations. The difference between the average system acceleration and each generator site acceleration is calculated for each fault condition. The average and standard deviation of the previously calculated differences are determined for each generator site over the entire population of faults. Equation 4.5 expresses this average ($\dot{\omega}^*$), where m is the number of faults studied,

$\bar{\dot{\omega}}$ is the average system acceleration and $\dot{\omega}_{ik}$ is the maximum acceleration calculated at generator i for fault k.

$$\dot{\omega}^* = \frac{\sum_{k=1}^{m} \left| \bar{\dot{\omega}} - \dot{\omega}_{ik} \right|}{m} \tag{4.5}$$

Table 4.4 shows the results of these studies with a listing of generator group locations in order of their degree of variation from the system average acceleration. Generator locations identified as responding close to the system average include Priest Rapids, Ice Harbor, Grand Coulee and Wanapum generator stations. Appendix D contains figures that show rotor angle accelerations for these generator sites, and the current brake controller input locations of John Day and Chief Joseph, compared with the average rotor acceleration for each fault.

Heavy Spring Generator	kV	Avg.	std.	Light Autumn Generator	kV	Avg.	std.
WANAPUM	13.8	1.661	3.250	ROCKY RH	15.0	1.876	1.776
PRIEST R	13.8	2.170	1.483	COULEE51	15.0	2.054	1.319
PRIESTR2	13.8	2.631	1.230	PRIESTR2	13.8	2.548	1.401
ICE H1-2	13.8	2.899	3.352	ROCK IS2	6.9	2.623	1.675
ICE H5-6	13.8	3.447	3.095	CHIEF JO	13.8	2.631	2.996
ROCK IS2	6.9	3.491	1.974	MCNARY 2	13.8	3.288	2.584
COULEE 2	13.8	3.649	2.572	COULEE 2	13.8	3.309	4.038
COULEE52	15.0	3.818	3.241	MCNARY 1	13.8	3.421	2.201
COULEE52	15.0	3.830	3.288	CHIEF J5	13.8	3.807	4.659
MCNARY 1	13.8	3.961	3.451	WELLS	14.4	4.154	2.716
COULEE51	15.0	3.968	3.411	ROUND BU	13.8	5.133	3.053
ROCKY RH	15.0	4.247	5.026	LOW GRAN	13.8	5.166	2.863
WELLS	14.4	4.333	2.269	LIT GOOS	13.8	5.177	2.841
RRCH8-11	15.0	4.559	5.201	LOW MON	13.8	5.333	2.755
MCNARY 2	13.8	4.591	3.475	WANAPUM	13.8	5.487	4.867
MCNARY 2	13.8	4.591	3.475	BONN PH2	13.8	5.560	4.049
BONNVIL2	13.8	5.138	4.006	DIABLO	13.8	5.699	2.894
ICE H3-4	13.8	5.176	4.496	JOHN DAY	13.8	5.778	4.086
BONNVIL1	13.8	5.629	4.149	HUNGRY H	13.8	6.895	4.075
TEXWEST1	13.8	5.663	6.763	LIBBY	13.8	7.338	2.990
TEXWEST2	13.8	5.663	6.763	DALLES 3	13.8	7.927	5.729
TEXWEST3	13.8	5.677	6.994	NOXON 5	14.4	8.154	10.512
CHIEF JO	13.8	6.021	6.911	ASHE 2	25.0	8.286	6.709
CHIEF J5	13.8	6.125	8.003	CENTR G1	20.0	9.409	9.722
LOW GRAN	13.8	6.339	8.893	CENTR G2	20.0	9.531	9.805
DWOR 1-2	13.8	6.342	7.692	ICE H3-4	13.8	10.293	8.779
DIABLO	13.8	6.359	3.309	PELTON	13.8	11.067	8.878
CHIEF J2	13.8	6.387	7.856	BOARD F	24.0	13.478	11.647
ENSERCH4	13.8	6.610	6.766				
ENSERCH1	13.8	6.657	6.125				
ENSERCH2	13.8	6.657	6.125				
ENSERCH3	13.8	6.657	6.125				
LIT GOOS	13.8	6.743	7.590				
LOW MON	13.8	6.816	6.405				
DALLES 1	13.8	6.866	3.049				
BOUNDARY	14.4	7.056	5.751				
DWOR 3	13.8	7.075	10.319				
TEXWEST4	13.8	7.191	6.514				
CENTR G2	20.0	7.487	9.168				
CENTR G1	20.0	7.499	9.168				
BOUNDRY2	14.4	7.593	3.455				
ICE H3-4	13.8	8.049	6.636				
BONN PH2	13.8	8.194	7.643				
NOXON 5	14.4	8.445	7.064				
DALLES22	13.8	8.558	4.574				
DALLES21	13.8	8.580	4.573				
ROUND BU	13.8	8.710	4.516				
NOXON	14.4	8.815	6.917				
JOHN DAY	13.8	9.019	5.801				
HUNGRY H	13.8	9.103	3.412				
LIBBY	13.8	9.157	3.251				
ROSS 42	13.8	9.534	4.206				
ROSS 44	13.8	9.582	4.243				
TENASKA3	13.8	9.636	15.599				
TENASKA1	13.8	9.735	15.819				
TENASKA2	13.8	9.735	15.819				
DALLES 3	13.8	10.241	5.939				
WANAPUM2	13.8	11.134	9.376				
PELTON	13.8	11.748	7.622				
CAB GORG	13.8	15.195	24.283				
BOYLE	11.5	19.876	10.162				

Table 4.4 Variance of Generators from Average System

4.6. Conclusion

Results show that neither the Chief Joseph nor the John Day input locations are near the top of the list of those sites that most closely follow the system average acceleration. These input sites may still provide adequate, though not optimal, system coverage if for every fault studied one or both input locations have an equal or greater acceleration than the average system. (See Figure 4.3, 4.4) For the heavy spring cases studied the two current input sites do meet this requirement for adequate system coverage, though for many faults the magnitude of the site acceleration is much greater than that of the system average. For the light autumn cases studied there are several faults for which neither input site has a greater magnitude than the system average. A control system at these sites would need to be excessively sensitive to detect all faults for which BPA requires braking and hence may operate on faults that do not require braking, leading to unnecessary disturbances of the power system.

The center of the Northwest power system is in central Washington near Midway substation. Several generators in this area could provide system inputs which follow the average Northwest equivalent system response. Studies show that using two or more input locations chosen in this group provide a control system input more indicative of the average Northwest power system response than using the two current sites, Chief Joseph and John Day.

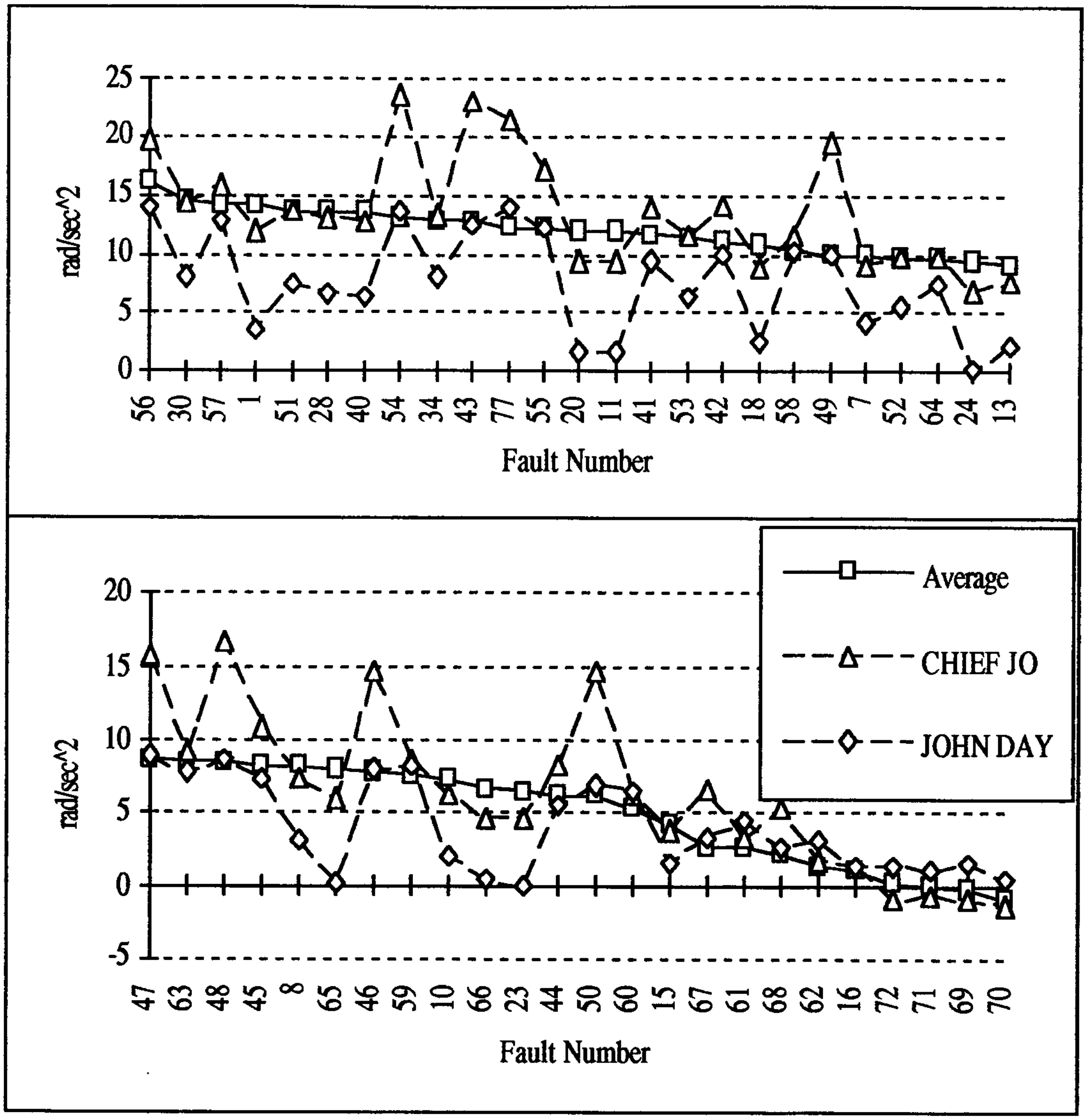

Figure 4.3 Light Autumn Case Chief Joseph and John Day Coverage

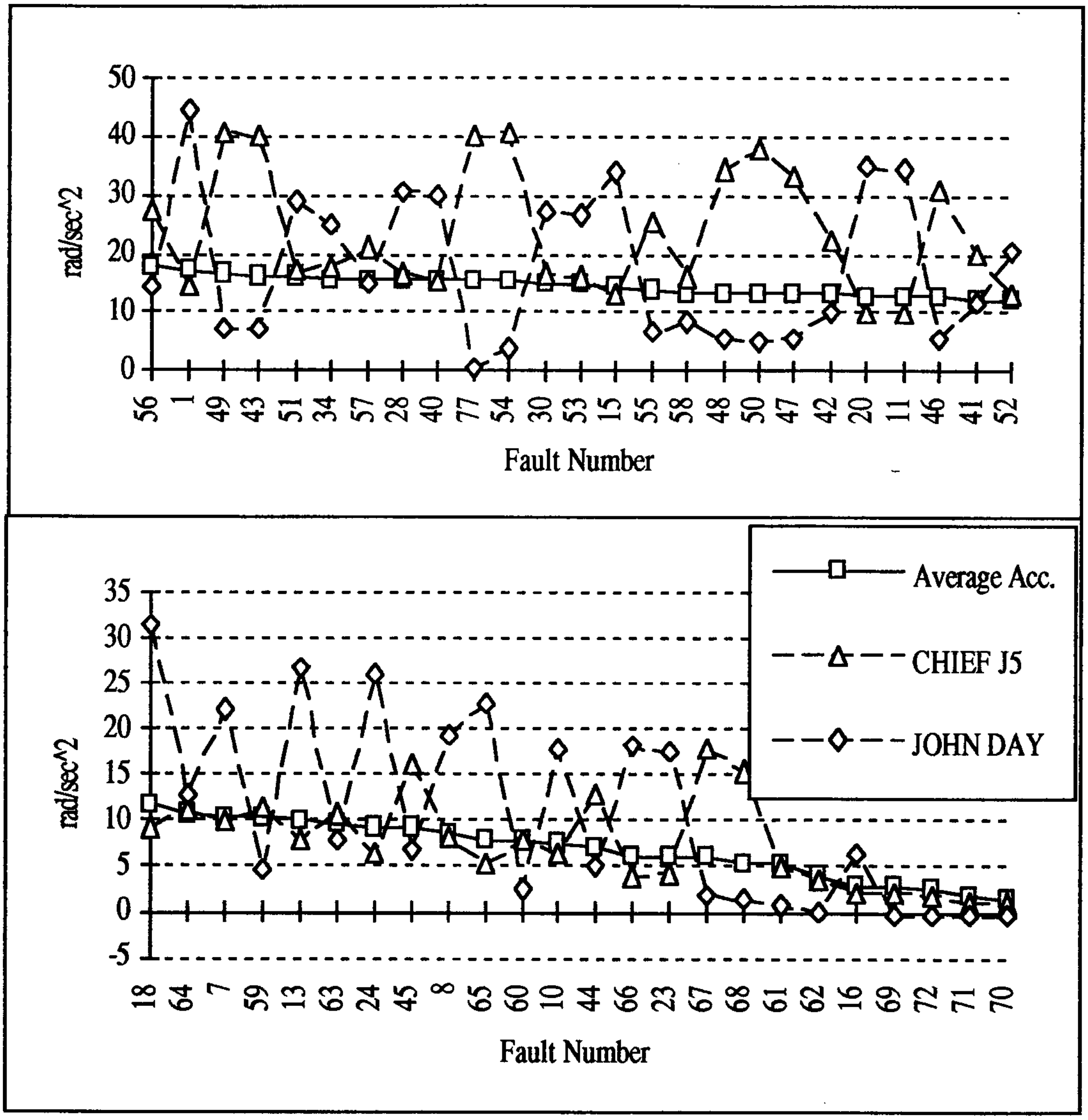

Figure 4.4 Heavy Spring Case Chief Joseph and John Day Coverage

CHAPTER 5 SIMULATION STUDIES OF BRAKE OPTIONS

5.1. EMTP Model Development

In studying power system transient response it is necessary to have an adequate computer model. Often, as in this project, many power system scenarios need to be evaluated in a short period of time, requiring simplified system models. The EMTP program is chosen to simulate the transient response of our power system model because of its structure and flexibility; it solves the differential equations associated with the power system. Generator models are of a high order to represent true dynamic interaction, and control algorithms can easily be evaluated by using modeling functions built into the program.

Two 5-generator EMTP models are the primary computer simulation tools in this thesis work. Figures 5.1 and 5.2 show the one-line diagrams of these models. Appendix A contains the EMTP code for these two models and controllers described in detail later in this chapter. The light loading spring condition model was the first developed. It was derived from a 4-Generator model developed by OSU and BPA. [10] The additional generator, associated transmission, and local load represent the Montana power system. Using this model as a base, generation and loading conditions are changed to represent a heavily loaded spring condition. These models represent the main area interconnections in the Western American power system and consist of simple transmission line models; no other dynamic control such as governors, power system stabilizers or automatic voltage regulators are incorporated. Thus, the models are most effective in analyzing first swing inter-area transient response of the power system. They are also effective in isolating the effects of dynamic braking on the Western power system.

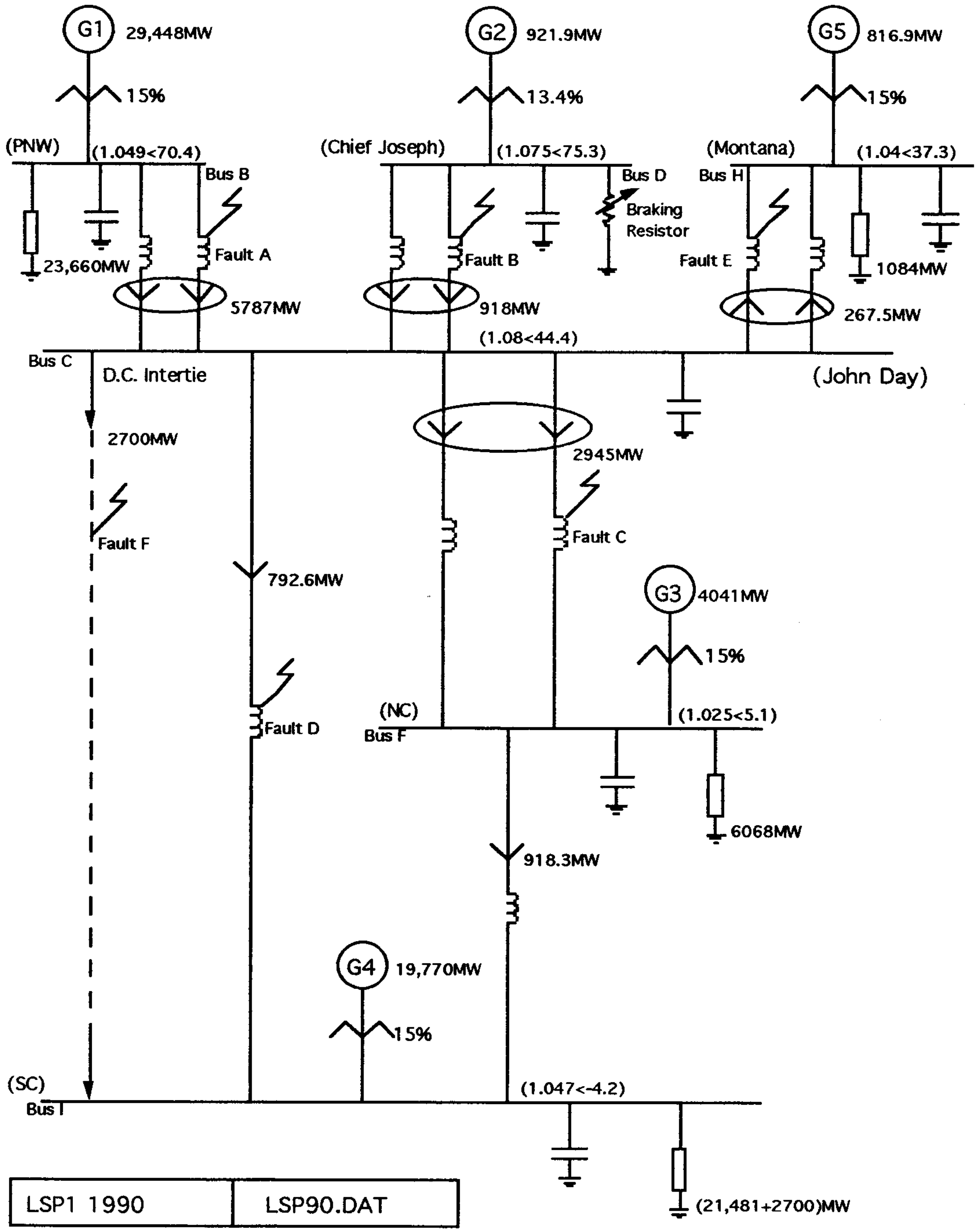

Figure 5.1 Light Spring Loading 5-Generator EMTP Model

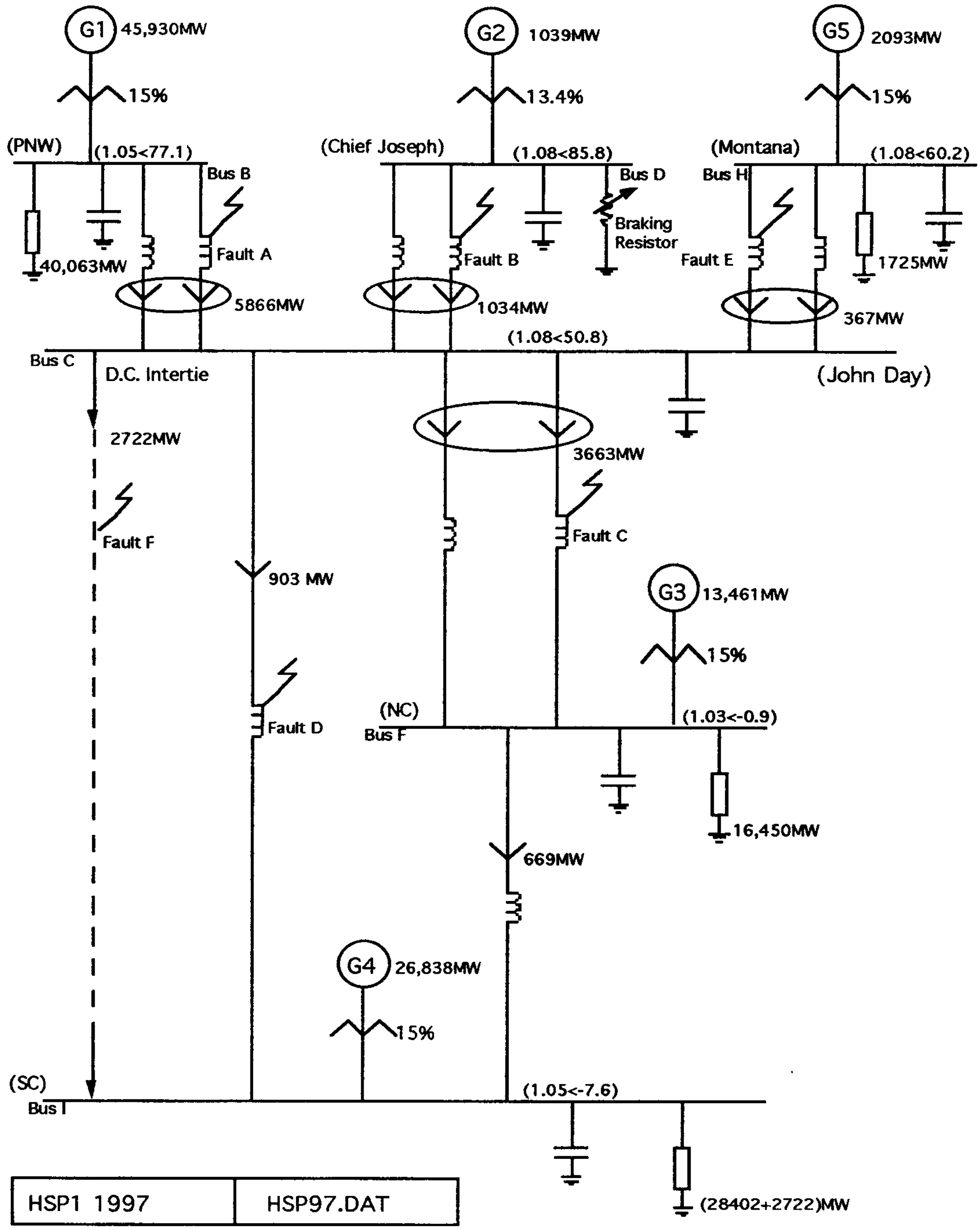

Figure 5.2 Heavy Spring Loading 5-Generator EMTP Model

5.2. Initial 3ø Braking Fault Study

To evaluate the operation of the two EMTP models and investigate the current use of the brake in the power system a fault study was performed. A fault is implemented by inserting a small impedance between all three phases and ground at the specified location. The fault duration is 1.5 cycles, at which time switches open to clear the faulted line section. This line section remains open for 20 cycles during which the fault is removed. Table 5.1 lists the faults evaluated in this study. Fault locations are also identified in Figs. 5.1 and 5.2. These faults represent interruptions of main interarea power transfers in the Western U.S. power system.

Faults Studied	
Fault A:	John Day-Northwest Fault
Fault B:	John Day-Chief Joseph Fault
Fault C:	John Day-Northern California AC Intertie Fault
Fault D:	John Day Southern California 3rd AC Intertie Fault
Fault E:	John Day-Montana Eastern Intertie Fault
Fault F:	DC Intertie Monopole Outage

Table 5.1 Fault studies implementing 3ø Braking

Fault study results illustrate the lack of system damping present in these models. The actual power system contains more system damping, which would help attenuate the second and subsequent oscillations of the disturbance much more quickly. However, the first swing of the EMTP models is still representative of the actual inter-area response of the power system.

The heavy spring model is not as useful for analyzing system disturbance response as the light spring model. Large amounts of generation, loading, and power transfer excessively stress the heavy spring model. Any disturbance of this model immediately makes the system unstable. The model provides some understanding during the first swing analysis, but needs modifications before further use in power system studies.

A good understanding of dynamic braking is obtained by analyzing the results of the fault studies using the light spring model. For the faults investigated, the use of a full 30 cycle brake application proves to be more harmful to the system than helpful. Long brake applications cause the Chief Joseph generator to separate from the rest of the power system. In the actual power system a longer brake application may be possible without separation due to the stronger system connections with Chief Joseph. There is still a limit in the actual power system, and hence a 30 cycle brake application may be doing more harm than good for most system faults.

Studies also show that controlling the duration of brake application can be effective in properly damping different system disturbances. For example, with the John Day-Chief Joseph fault, a 10 to 15 cycle brake application provides the best reduction in the Northwest generator swing, while with the John Day-Northern California fault a 5 to 10 cycle brake application is best.

5.3. 3ø Breaker Switched Control

Switching the brake with circuit breakers is the first switching control investigated. All three phases switch together for a balanced brake application. The limitation in using circuit breakers is the delay time required to switch on the brake and the longer delay time to interrupt the current flow through the breaker and switch off the brake. This delay time is not modeled in the following examples, but it should be understood that there is a minimum time, approximately 6 cycles, that a controller requires to insert and then remove the brake.

The effect of braking with two different controllers is examined. The first controller (Con1) uses inputs of output power from Chief Joseph and Northwest generators. The controller inserts the full brake when the relative velocity, calculated from generator power, at the Northwest generator exceeds 0.5 rad/sec. The brake remains inserted until the relative velocity calculated at the Chief Joseph generator drops below -0.7 rad/sec. This first controller inserts the brake only once. Figure 5.3 illustrates this controllers' logic.

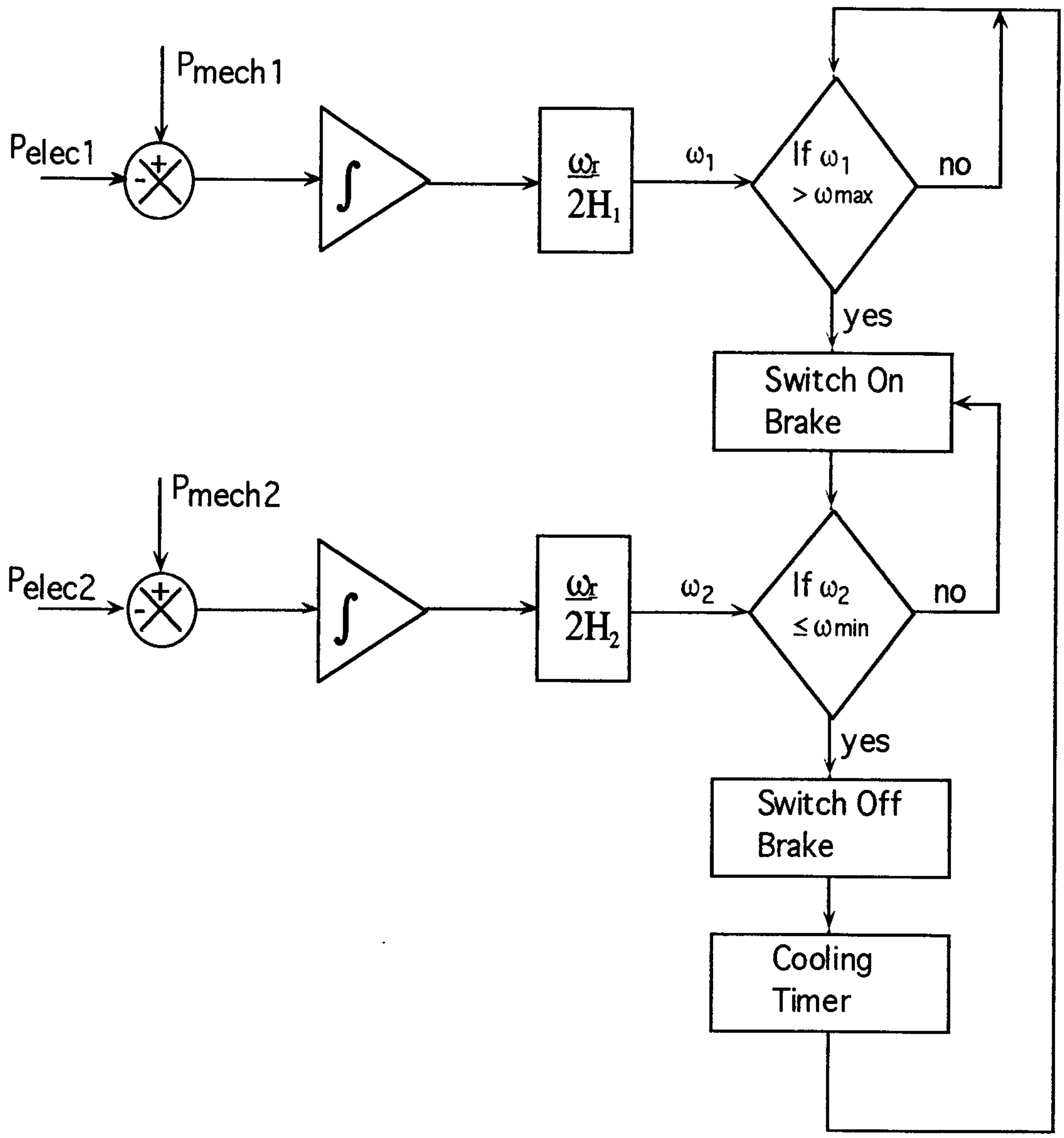

Figure 5.3 Brake Controller 1 (Con1): Generator 1 = Northwest, Generator 2 = Chief Joseph

The second controller (Con2) operates the same as Con1 to insert the brake for the first time, but allows for the insertion of the brake a second time during the first swing of the system. Once the controller removes the brake after the first insertion, it waits until the relative velocity calculated at Chief Joseph exceeds 0.5 rad/sec. The brake is again inserted and remains inserted until the relative velocity at Chief Joseph drops below 0 rad/sec. Figure 5.4 illustrates this controllers' operation.

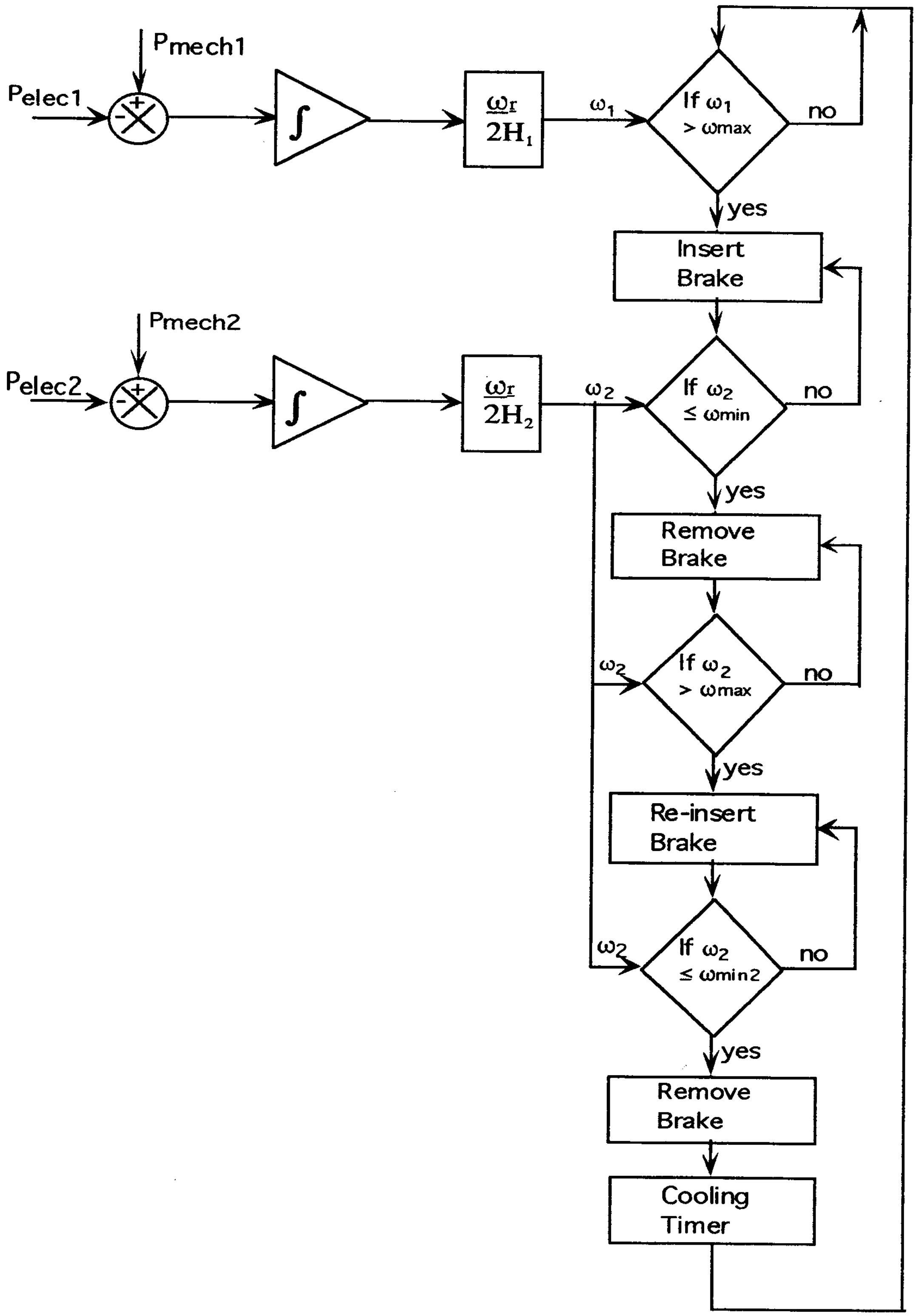

Figure 5.4 Brake Controller 2 (Con2): Generator 1 = Northwest, Generator 2 = Chief Joseph

The operation of these controllers is observed using the light spring 5-generator model. Three different faults are applied in this testing, including an inner Northwest area fault between Chief Joseph and John Day (Figs. 5.5 and 5.6), an AC Intertie fault between John Day and Northern California (Figs. 5.7 and 5.8), and a 3rd AC Intertie Fault between John Day and Southern California (Figs. 5.9 and 5.10). The key performance indicators for the brake, Northwest generator relative velocity, Chief Joseph generator relative velocity, Northwest-Southern California relative angle, and Chief Joseph-Southern California relative angle, are observed for each of the faults. Appendix E gives the other generator relative velocities and additional relative angles. Each figure shows the effect of no brake control, and dynamic brake control with the two controllers.

For all three fault conditions, the brake controller Con2 provides the best damping. This is illustrated in the Northwest generator velocity first swing reduction in Figs. 5.5, 5.7, 5.9. These figures also show the effect of brake application at the Chief Joseph generator. Chief Joseph generator remains in synchronism with the other system generators through all three faults, demonstrating the ability of these controllers to provide necessary, but not excessive, braking. The effect of dynamic braking is also observed in the reduction of first swing angle between the Northwest and Southern California generators shown in Figs. 5.6, 5.8, 5.10.

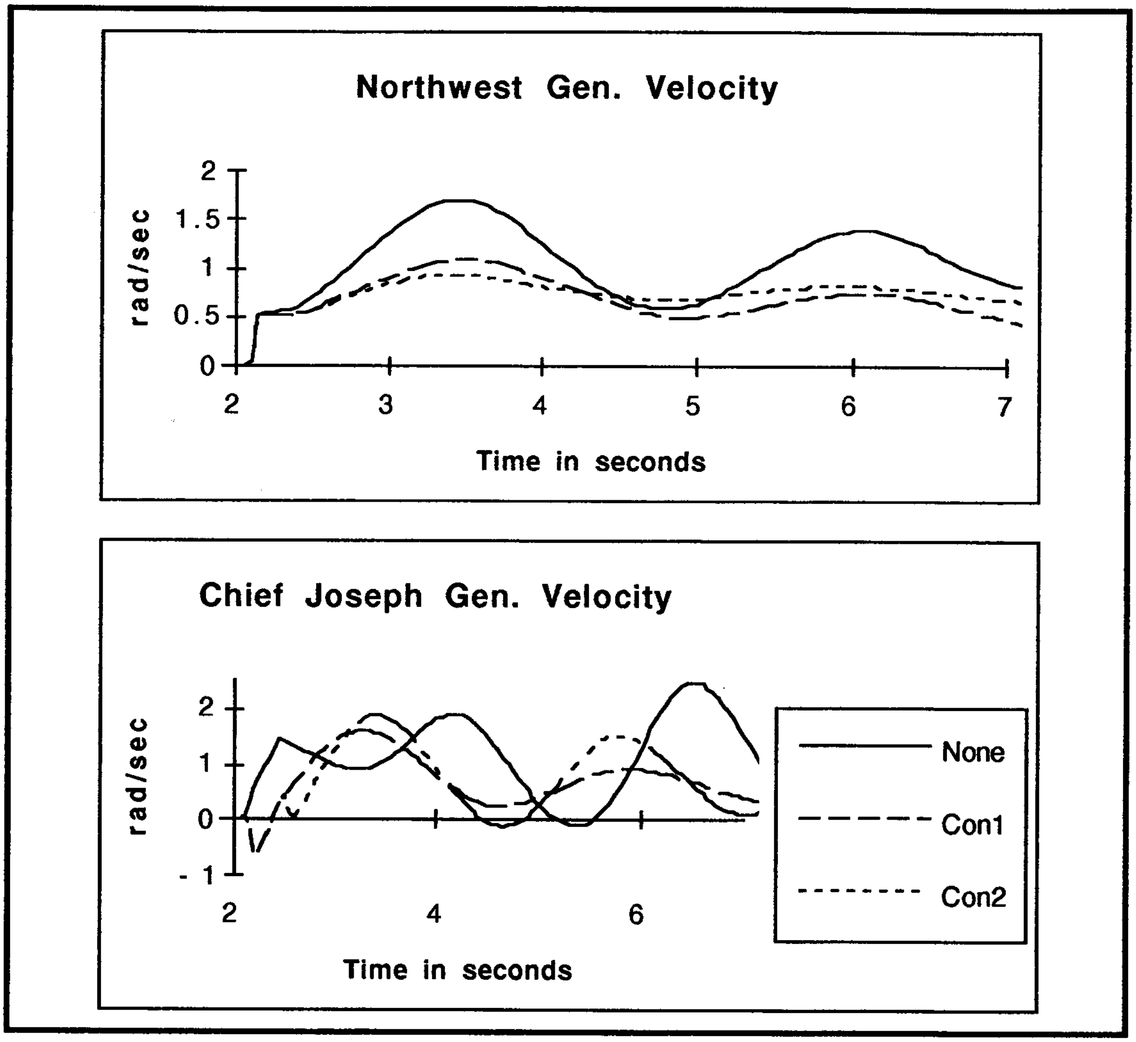

Figure 5.5 Relative Generator Velocities for John Day-Chief Joseph Fault

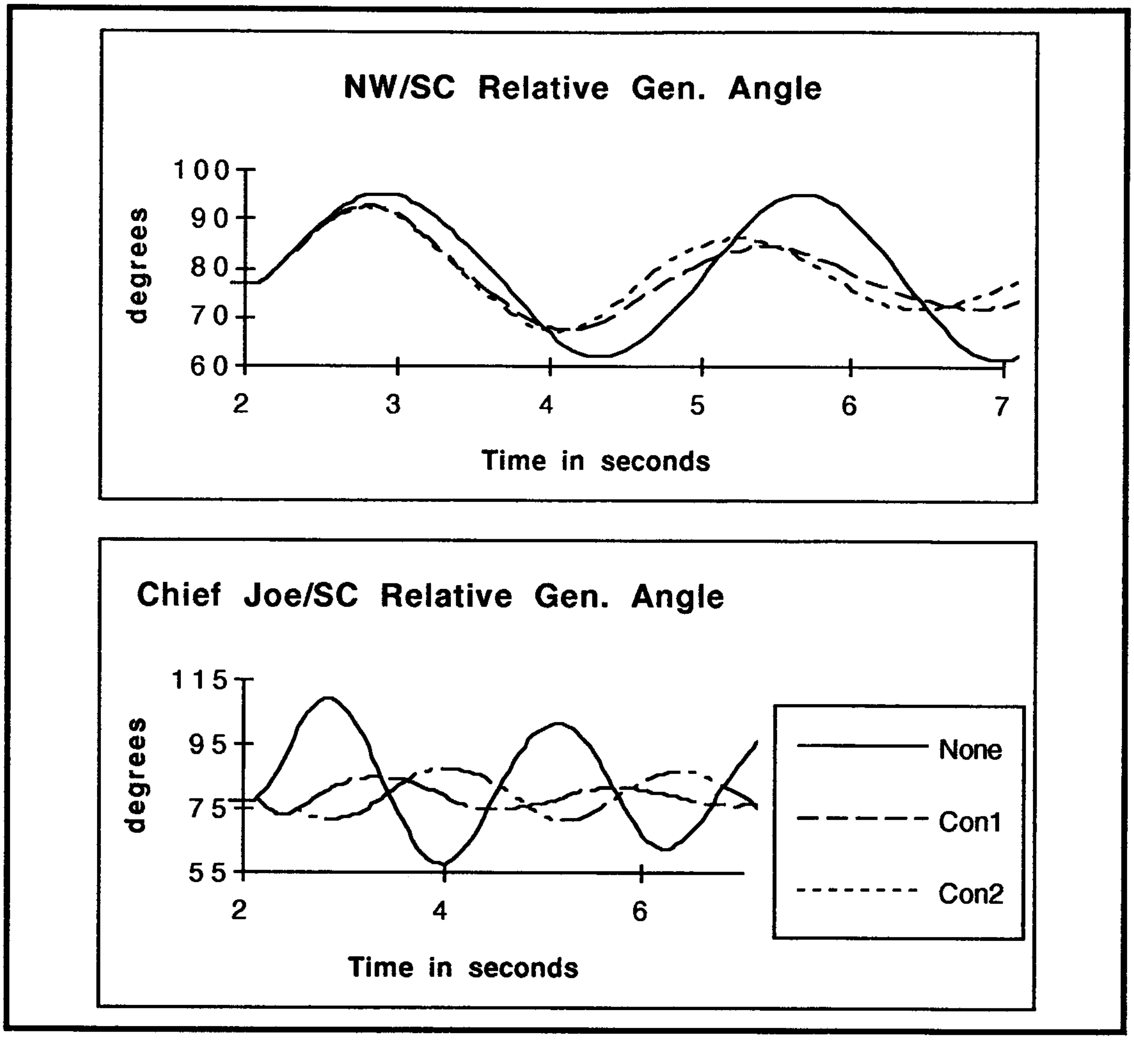

Figure 5.6 Relative Generator Swing Angles for John Day-Chief Joseph Fault

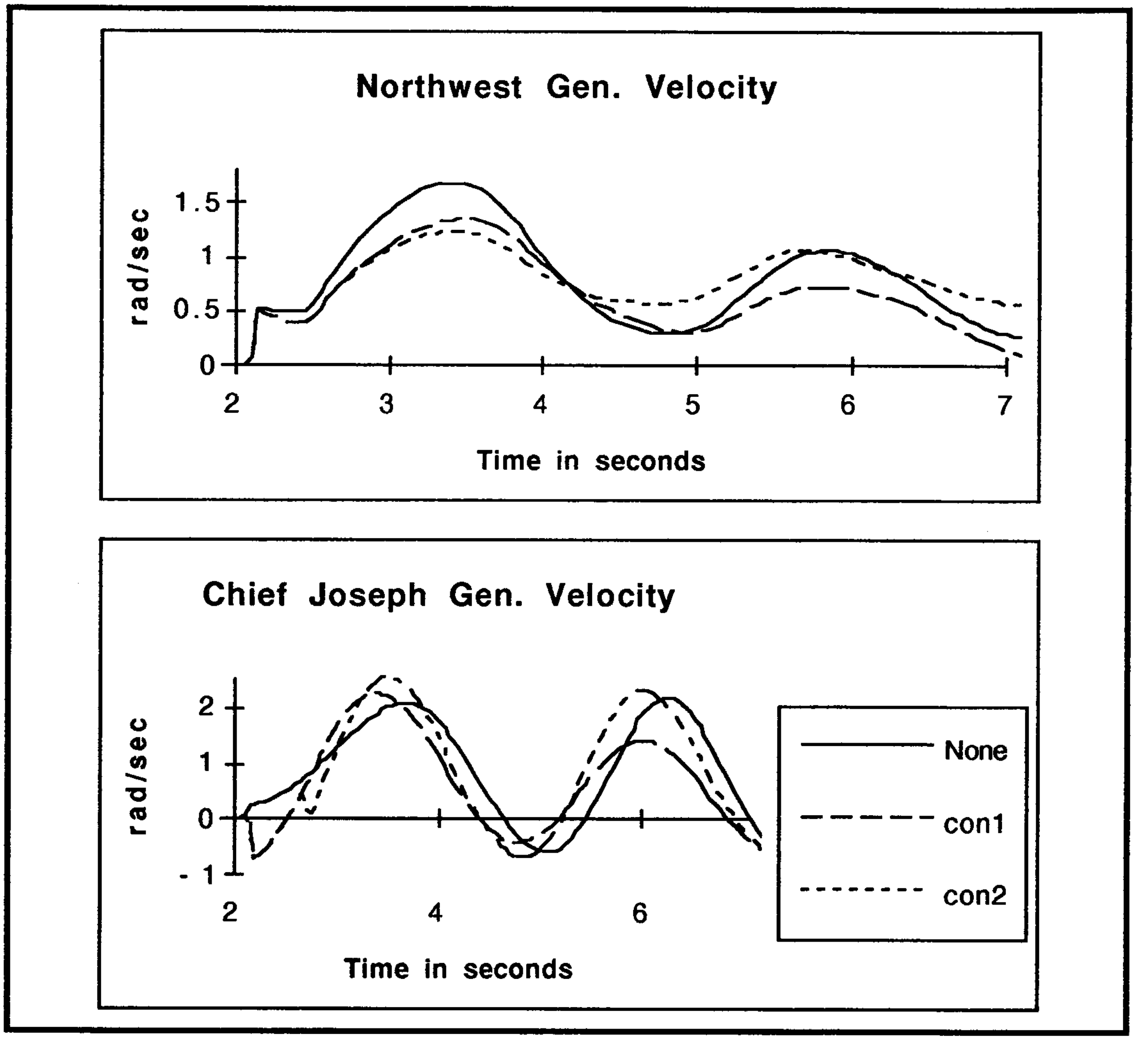

Figure 5.7 Relative Generator Velocities for John Day-Northern California AC Intertie Fault

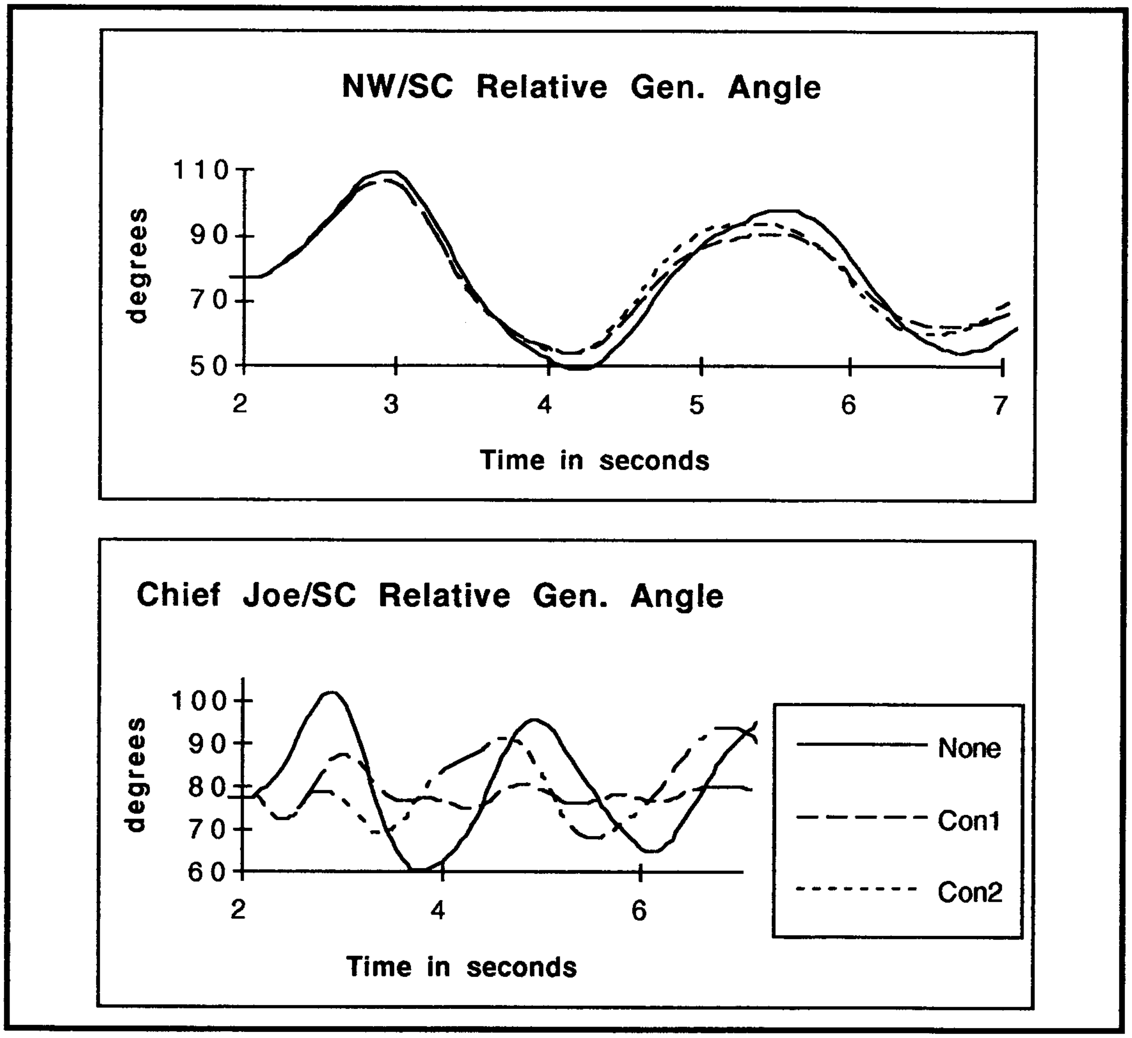

Figure 5.8 Relative Generator Swing Angles for John Day-Northern California AC Intertie Fault

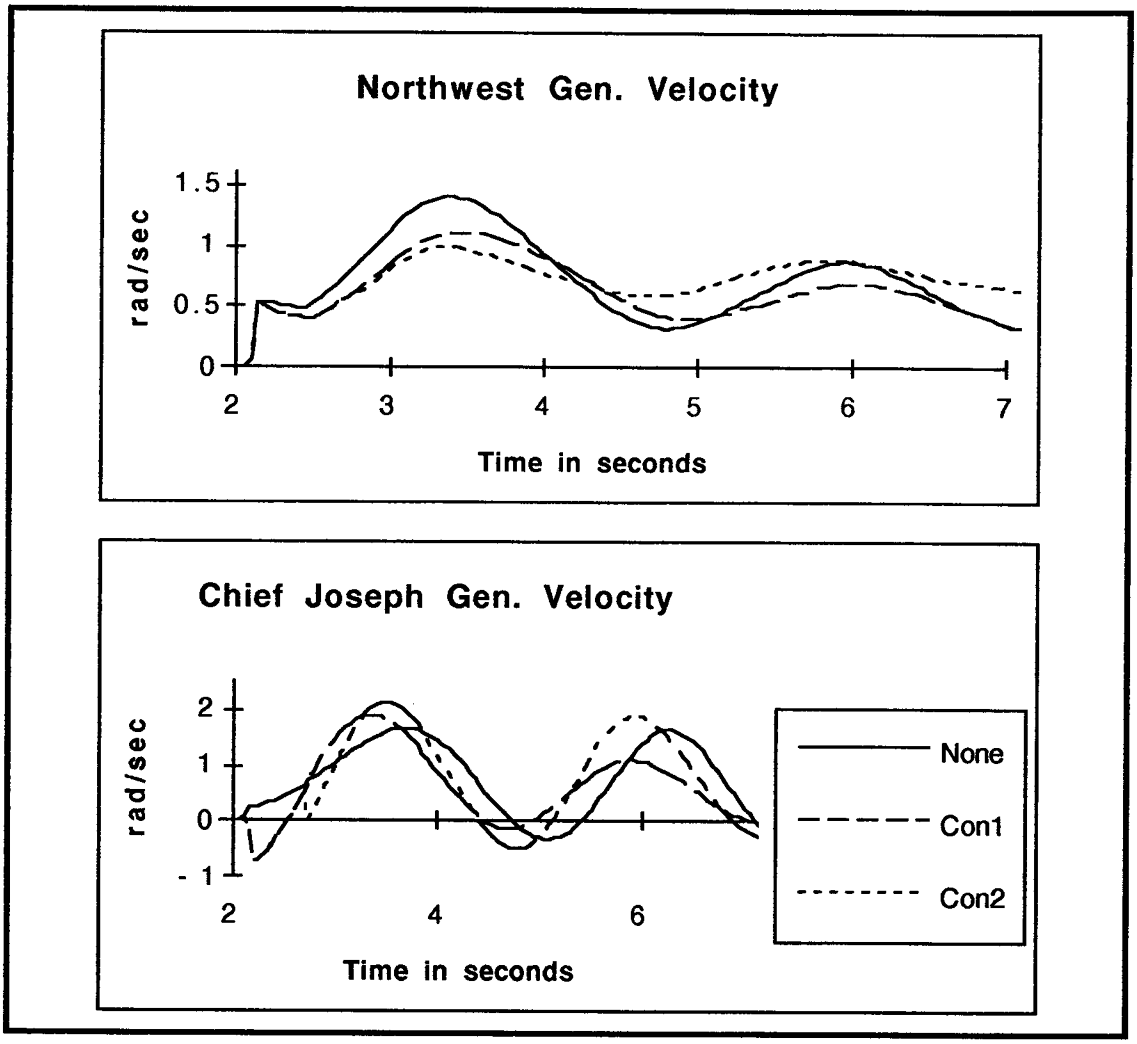

Figure 5.9 Relative Generator Velocities for John Day-Southern California 3rd AC Intertie Fault

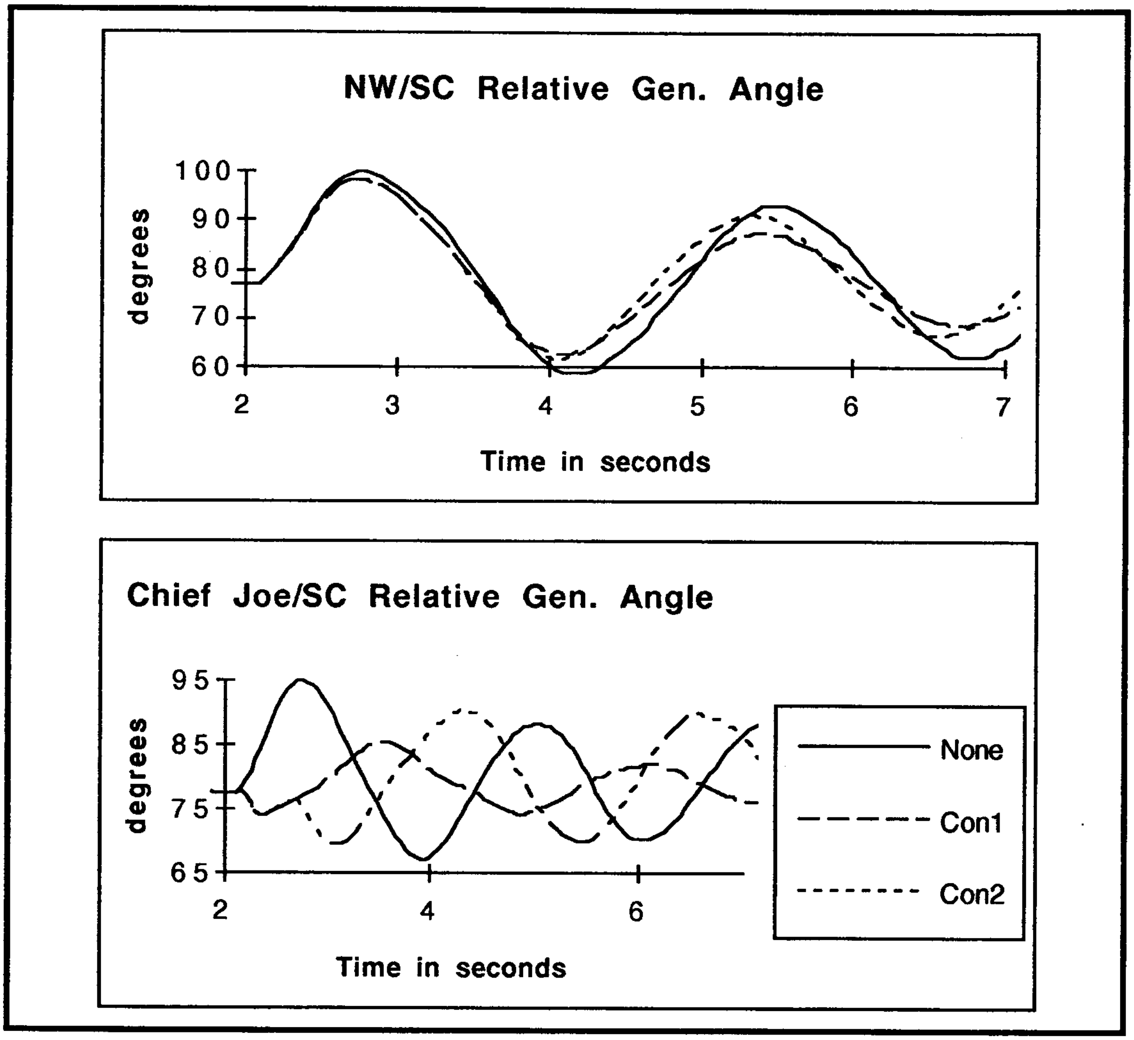

Figure 5.10 Relative Generator Swing Angles for John Day-Southern California 3rd AC Intertie Fault

5.4. 1ø Breaker Switched Control

Another possible switching method is the use of circuit breakers to switch individual phases of the braking resistor, thus allowing a controller to apply a fixed power brake in one third power increments. This gives added flexibility in varying the brake power dissipation for different magnitudes of disturbances. It also allows a stepped reduction in power after initial brake application as described in Chapter 3. The only concern in applying the brake in this manner is the effect of the unbalanced load. The imbalance may cause large zero and negative sequence currents to flow in transmission lines near the brake. Unintended operation of relays that operate on zero or negative sequence currents could trip transmission lines, thus disrupting system dynamic braking, and potentially amplifying the original disturbance. Using the light spring 5-generator model, single phase switching of the brake is evaluated for three different faults. Positive, negative and zero sequence currents are measured in the transmission line between Chief Joseph and John Day. Table 5.2 shows the maximum rms zero and negative sequence currents during braking for each fault. Discussions with transmission engineers at BPA indicate that this level of zero and negative sequence currents should not cause unwanted relay operation. An example plot of the positive, negative and zero sequence currents during single phase brake application is shown in Fig. 11.

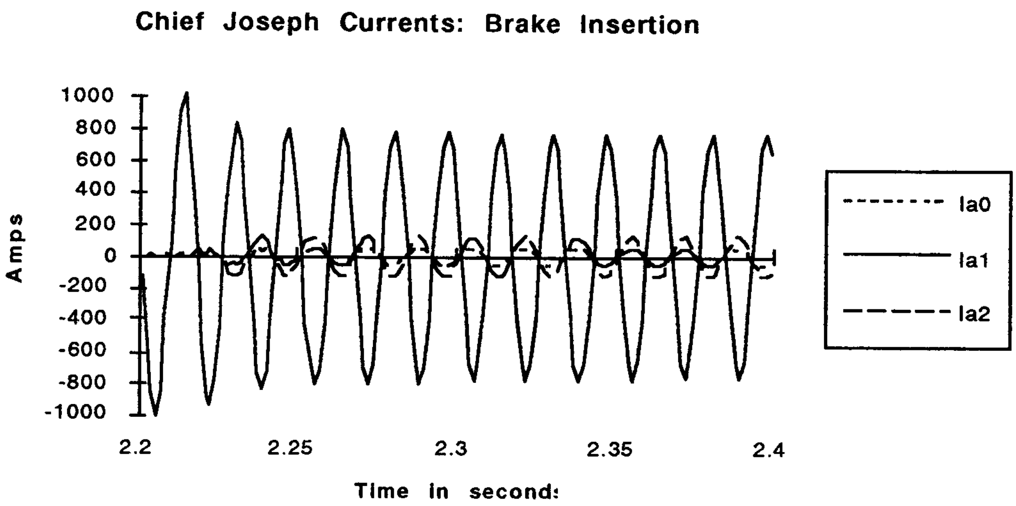

Figure 5.11 Chief Joseph-John Day Transmission Line Currents during Single Phase Resistive Brake Operation for John Day-Northern California AC Intertie Fault

Fault	Maximum Sequence Currents in Amps rms		
	Zero	Positive	Negative
John Day-Chief Jospeh	41.65	926.11	89.27
John Day-Northern California	62.55	1444.91	147.44
John Day-Southern California	62.23	1463.22	139.63

Table 5.2 Chief Joseph-John Day Transmission Line Currents during Single Phase Resistive Brake Operation

The operation of three controllers using single phase switching is investigated. Controllers Con1 and Con2, illustrated in Figs. 5.3 and 5.4, insert a single phase of the brake with a power dissipation of 467 MW. The control parameter ωmin is adjusted for these studies from -0.7 rad/sec to -0.5 rad/sec.

The third controller (Con3) takes advantage of the ability to vary brake power dissipation. Once the relative velocity at the Northwest equivalent generator exceeds ω_{max}, the maximum accelerating power measurement, for that generator, determines the fault severity. The controller uses two constants, K_1 and K_2, to scale the accelerating power input to determine the peak brake power. K_1 is used for the initial brake insertion and K_2 is used for the second brake insertion. The values of these constants are experimentally determined using the EMTP light spring model simulation. This controller uses a value of K_2 that is smaller than K_1 to provide a long duration reduced power second brake insertion.

A brake power reference level decreases exponentially from this initial power level. There are two time constants associated with the exponential decreasing brake power, τ_1 for the initial brake insertion and τ_2 for the second brake insertion. The values of these time constants are experimentally determined using the EMTP light spring model simulation, starting from a base time constant associated with the dominant intertie mode. τ_1 is slightly larger than τ_2 due to the short duration of the initial brake insertion. The brake controller approximates the exponentially decreasing brake power reference level by removing individual braking resistor phases. Hence a full variable power braking resistor is approximated in 467 MW steps from 0 to 1400 MW. Figure 5.12 provides an example of the single phase switching brake power output relationship to the brake power reference level. Figure 5.13 illustrates the control logic.

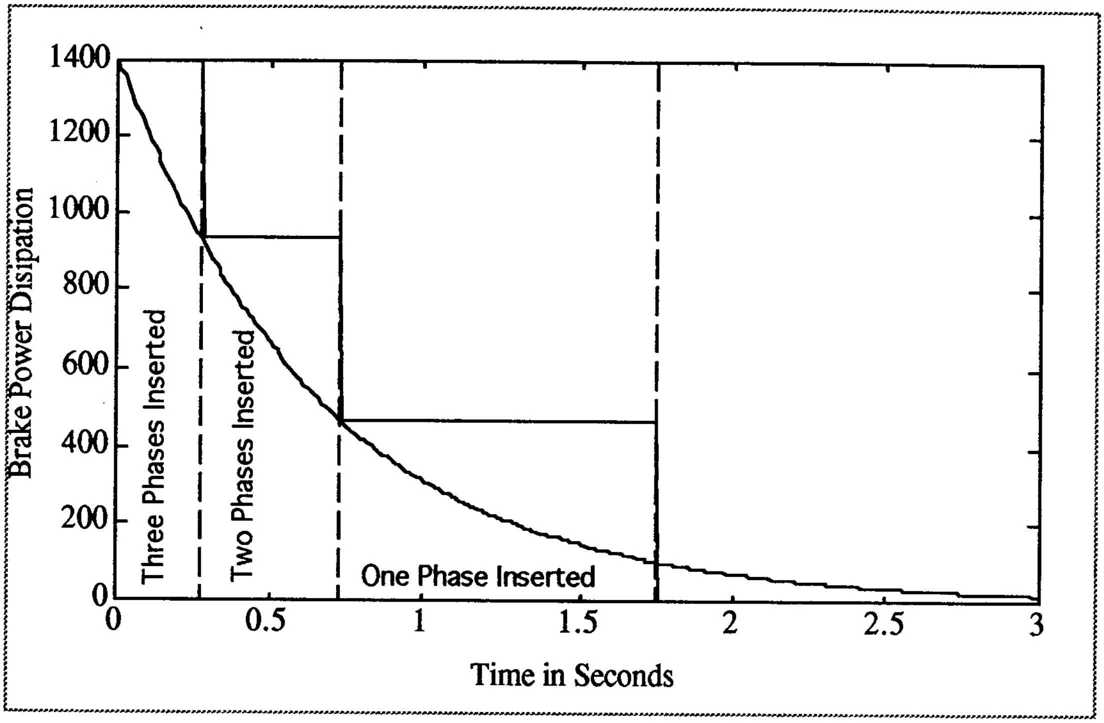

Figure 5.12 Single Phase Braking Representation of Exponentially Decreasing Brake Power

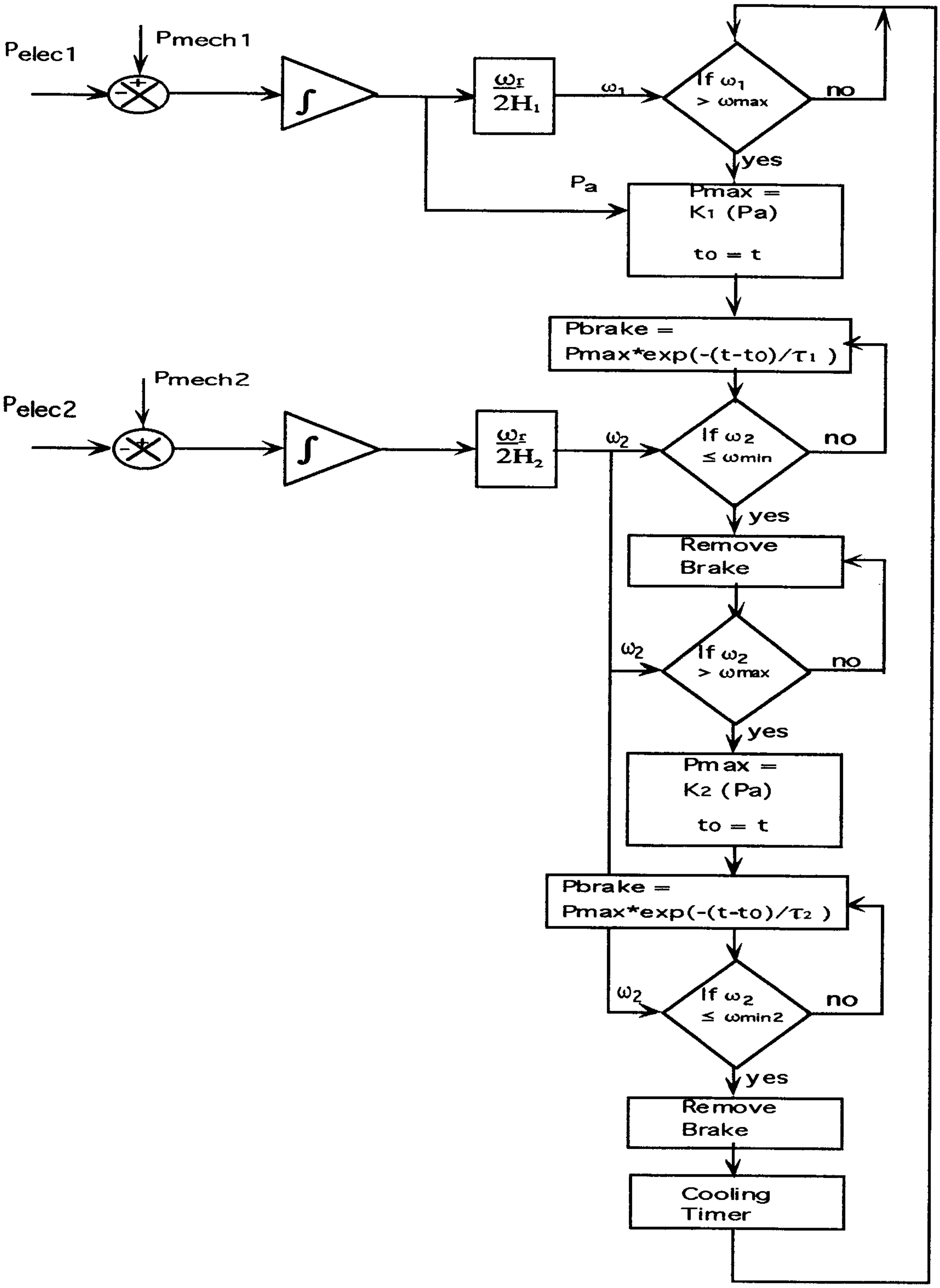

Figure 5.13 Brake Controller 3 (Con3): Generator 1 = Northwest, Generator 2 = Chief Joseph

The operation of these three controllers is observed using the light spring 5-generator model. The same faults, used in the three phase brake investigation, are again applied, including an inner Northwest area fault between Chief Joseph and John Day (Figs. 5.14 and 5.15), an AC Intertie fault between John Day and Northern California (Figs. 5.16 and 5.17), and a 3rd AC Intertie Fault between John Day and Southern California (Figs. 5.18 and 5.19). The key performance indicators for the brake as used in the three phase braking section are observed for each of the faults. Appendix E shows the other generator relative velocities and additional relative angles. Each figure shows the effect of no brake control, and dynamic brake control with the three controllers.

For all three fault conditions, the brake controller Con3 provides the best damping. This is illustrated in the Northwest generator velocity first swing reduction in Figs. 5.14, 5.16, 5.18. Chief Joseph generator remains in synchronism with the other system generators through all three faults, again demonstrating the ability of these controllers to provide necessary, but not excessive, braking. It is also interesting to observe the generator swing angle between Chief Joseph and Southern California generators, shown in Figs. 5.15, 5.17, 5.19. The long second brake insertion, enabled through a reduction in brake power, significantly reduces this generator swing angle.

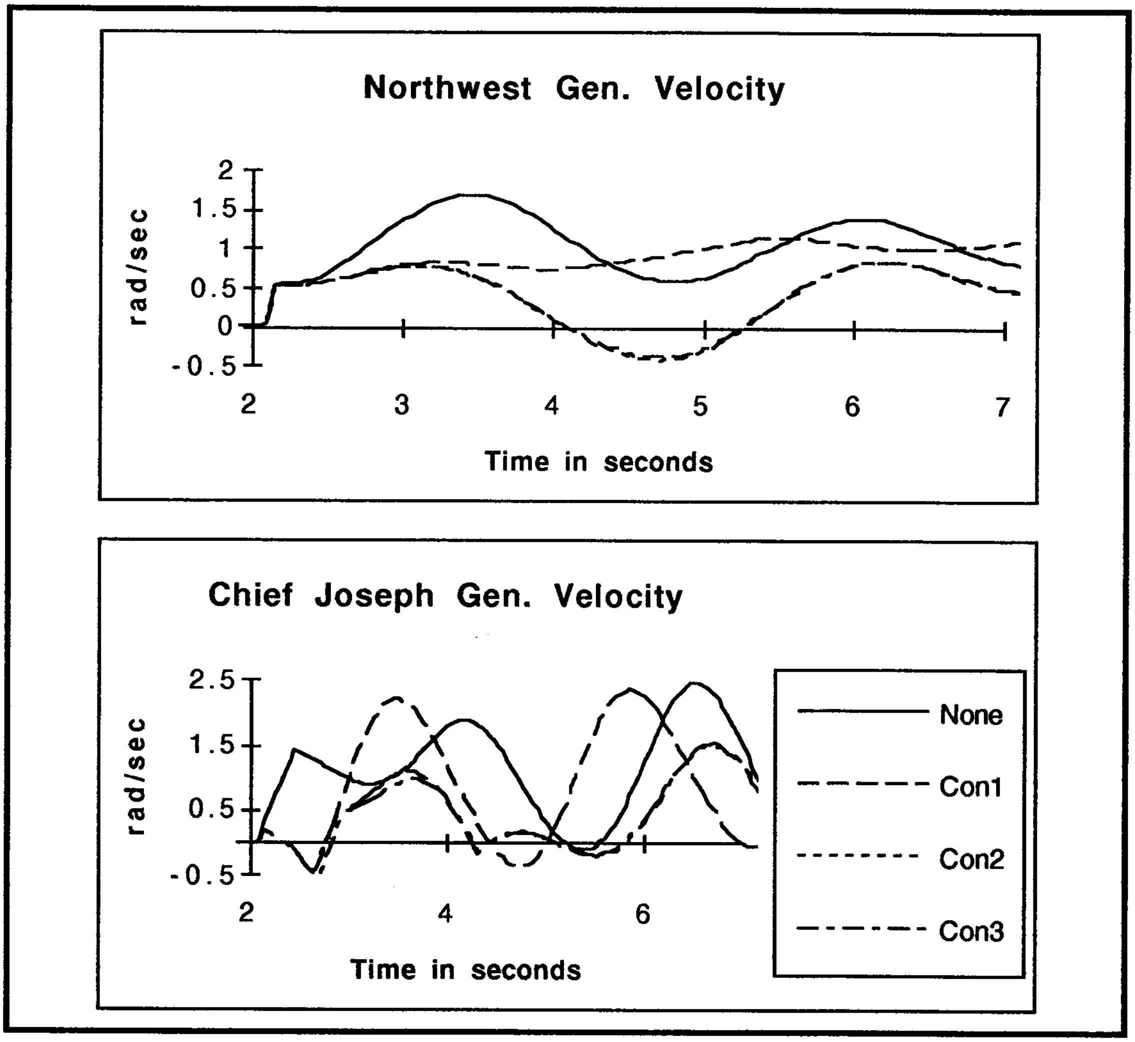

Figure 5.14 Relative Generator Velocities for John Day-Chief Joseph Fault

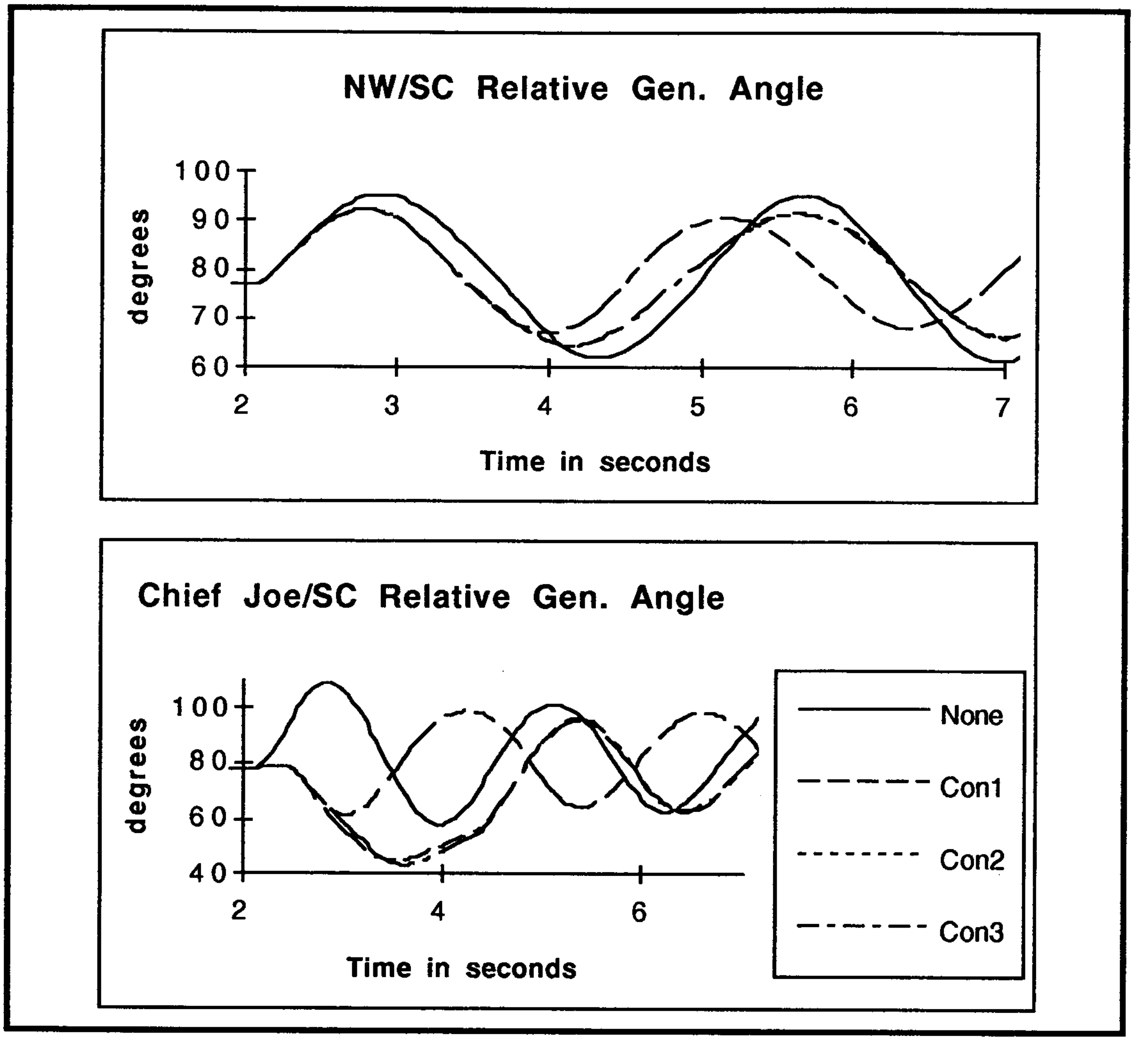

Figure 5.15 Relative Generator Swing Angles for John Day-Chief Joseph Fault

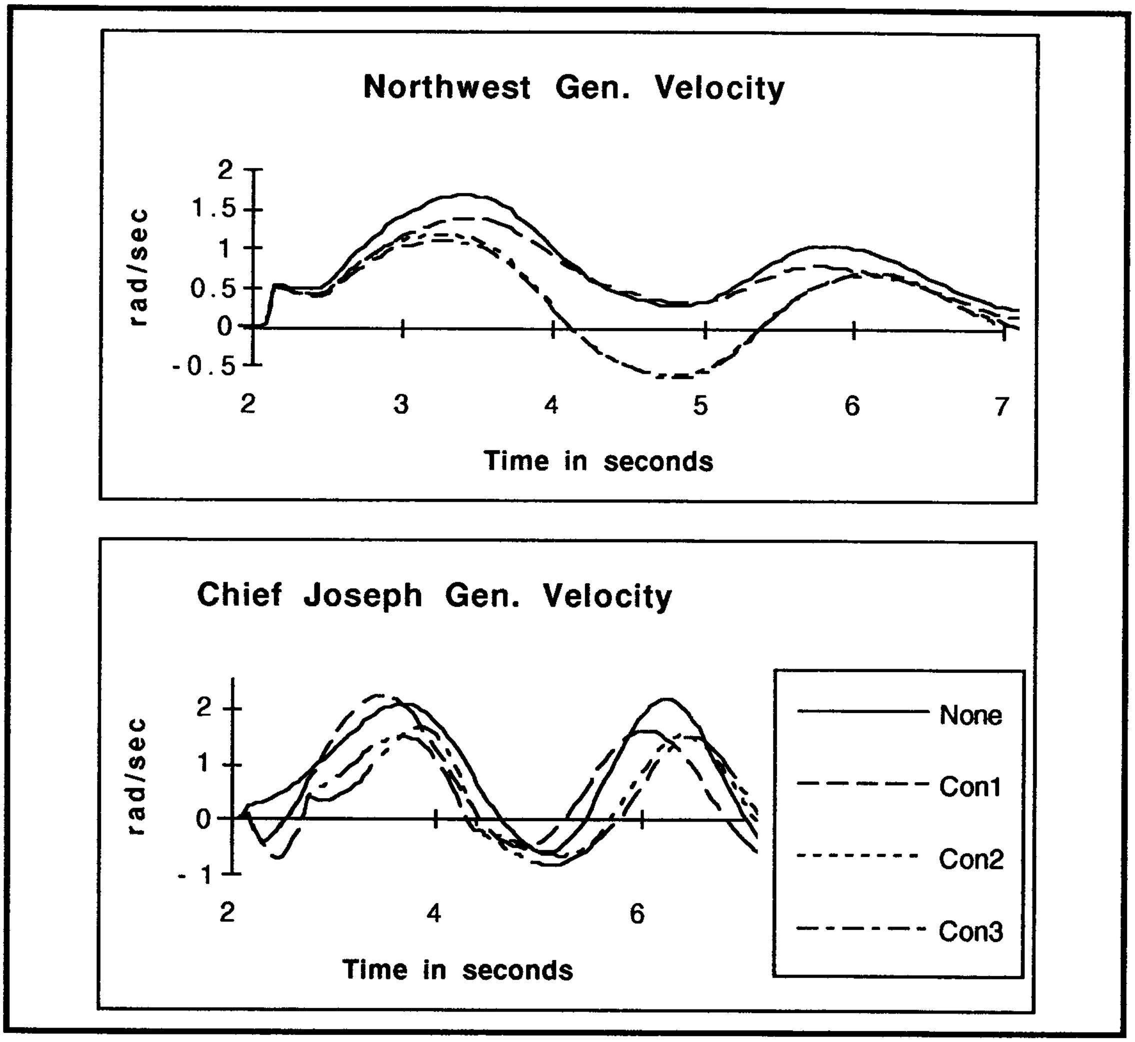

Figure 5.16 Relative Generator Velocities for John Day-Northern California AC Intertie Fault

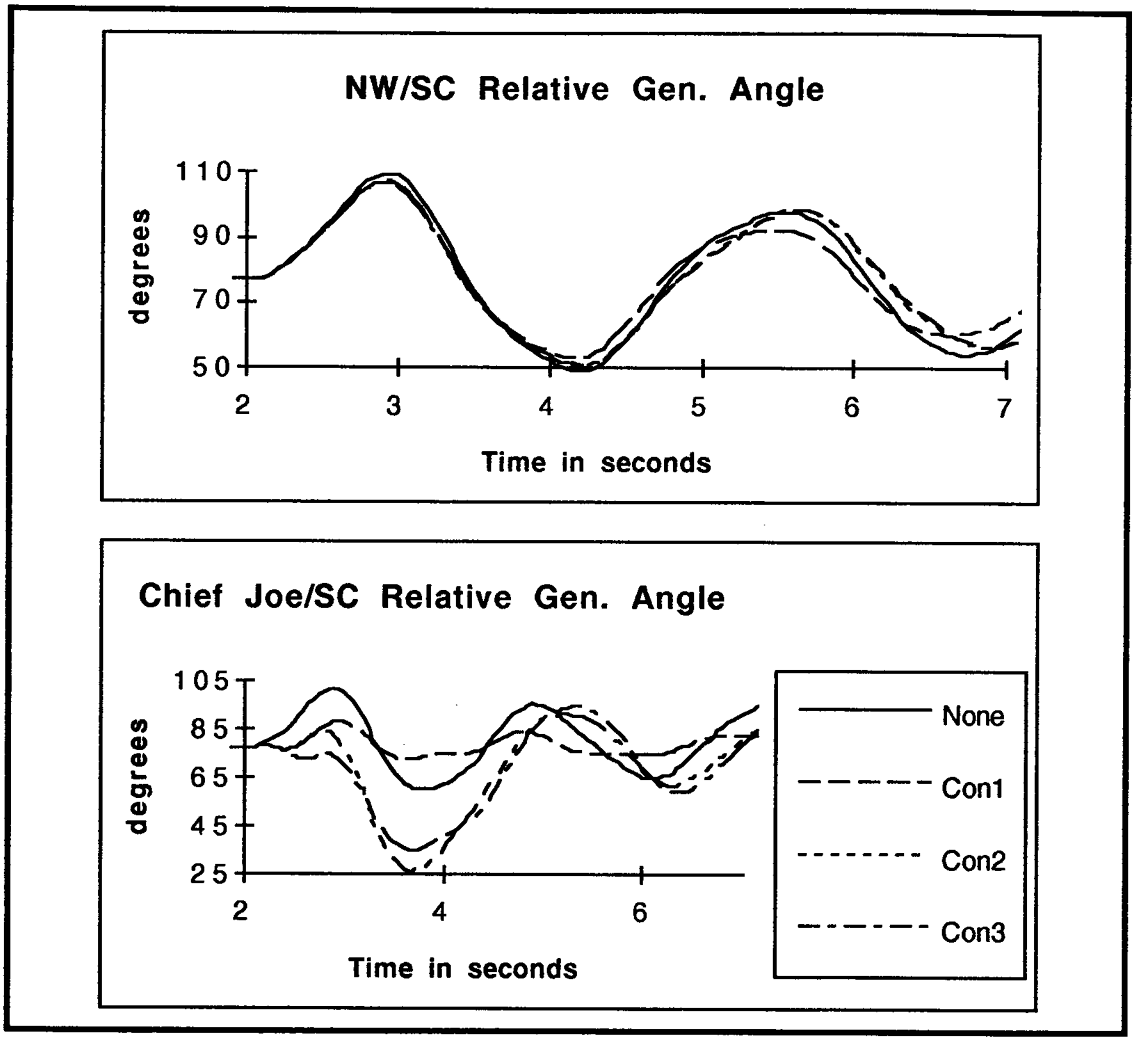

Figure 5.17 Relative Generator Swing Angles for John Day-Northern California AC Intertie Fault

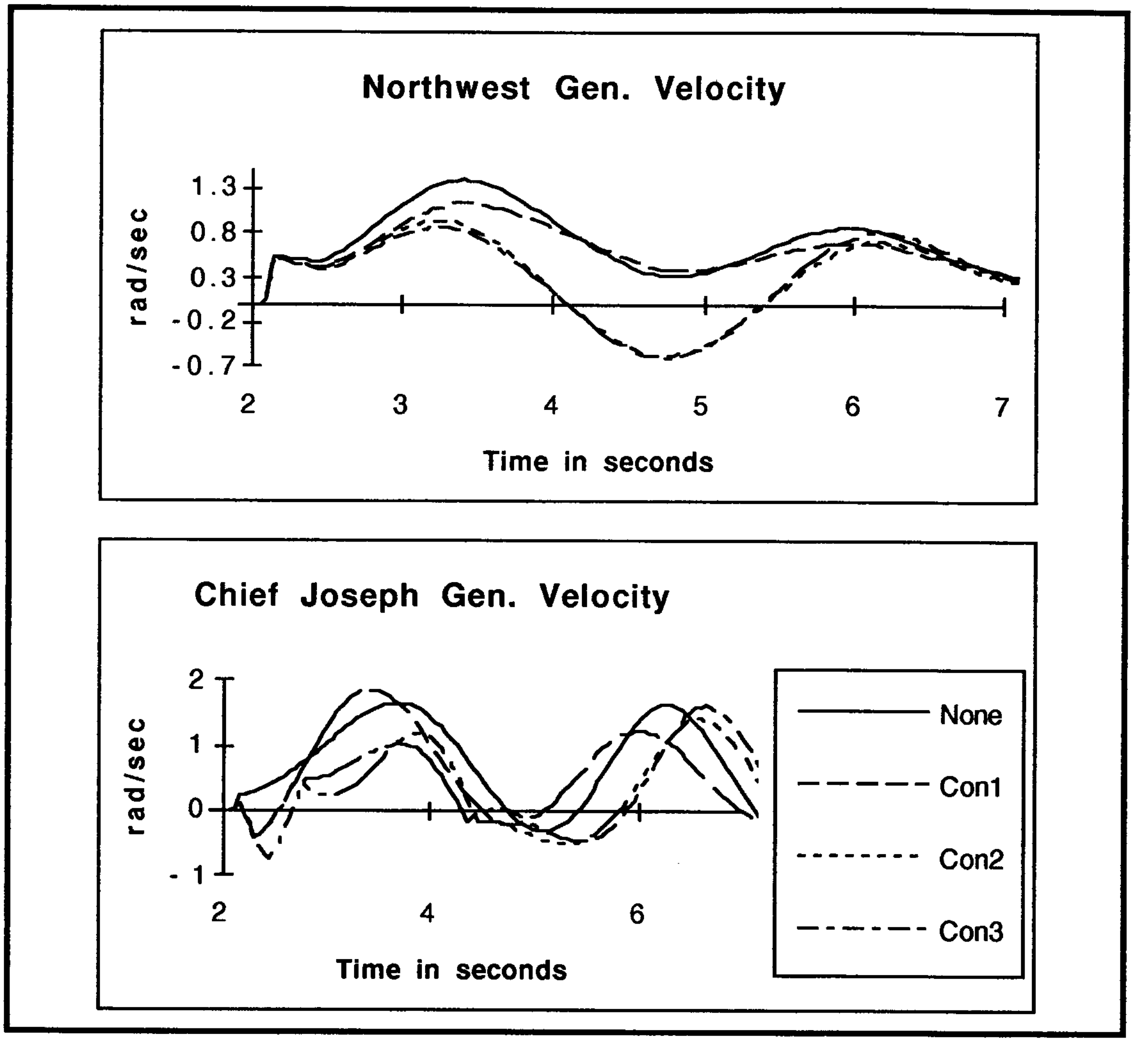

Figure 5.18 Relative Generator Velocities for John Day-Southern California 3rd AC Intertie Fault

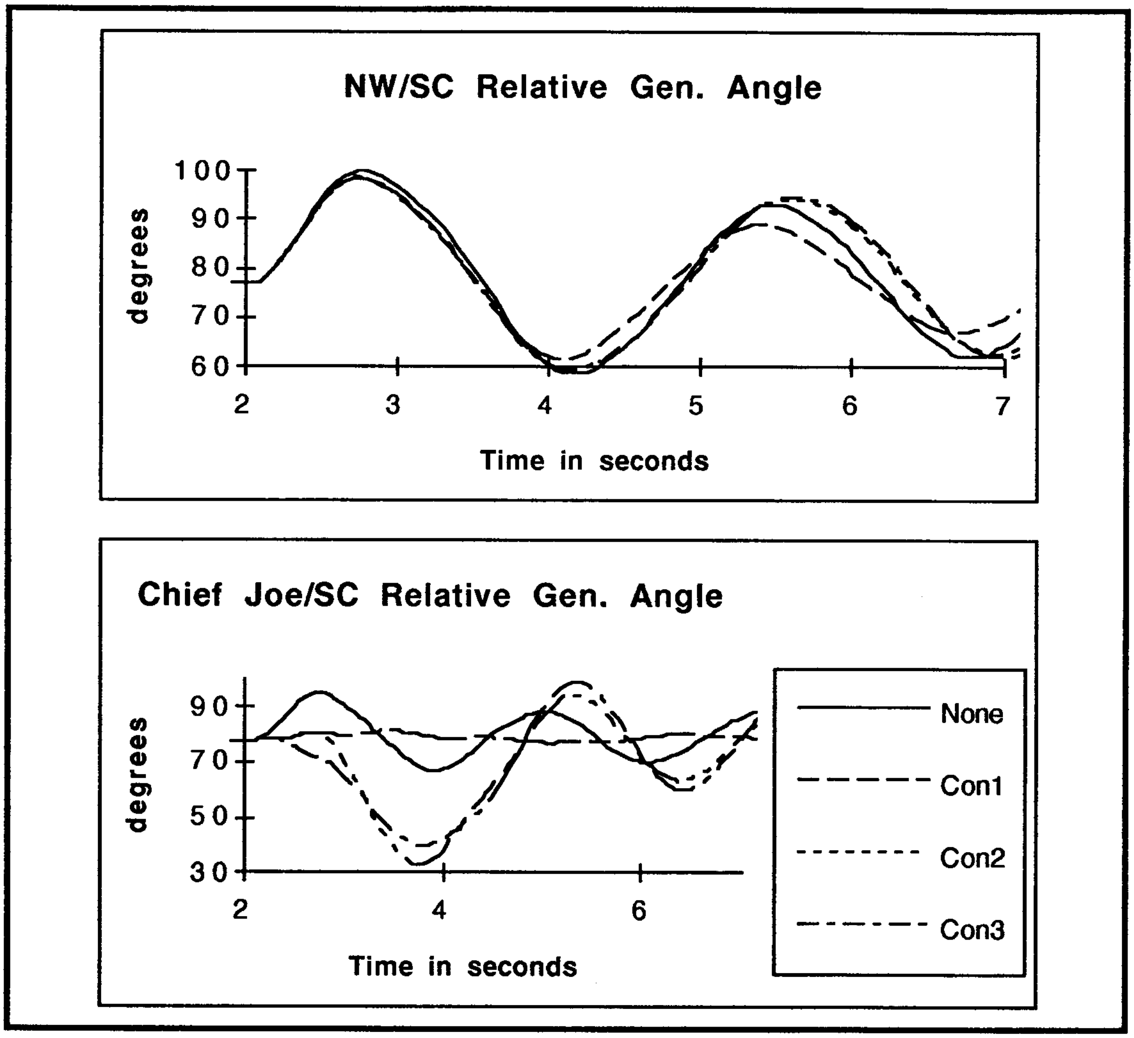

Figure 5.19 Relative Generator Swing Angles for John Day-
Southern California 3rd AC Intertie Fault

5.5. Thyristor Switched Control

Switching the braking resistor with thyristors allows for complete control over the power dissipation in the braking resistor. Utilities have used thyristors in power systems for high voltage DC conversion since the 1970's. Thyristors conduct when the anode of this device is positive with respect to the cathode and a current pulse is supplied to the gate. The device remains in a conduction state, regardless of gate current, until a reverse voltage bias appears across the device and the device current goes to zero. [11] Controlling the voltage applied across the resistor controls the power dissipation in the resistor. Varying the delay angle between a particular phase voltages' positive zero crossing and the time of applying a gate pulse allows control over the rms voltage across the braking resistor. Equation 5.1 describes the relationship of this delay angle (firing angle) to voltage applied across one phase resistor.

$$V_{br} = \frac{V_{ll}}{\sqrt{3}} \cdot \cos\left(\frac{\alpha}{2}\right) \tag{5.1}$$

The same controller used with the single phase switching, Con3, controls the thyristor switched braking resistor. The controller converts the desired brake power to a firing angle by equation 5.2.

$$\alpha = \frac{180^\circ}{\pi/2} \cdot \cos^{-1}\left(P_{brake}/P_{\max}\right) \tag{5.2}$$

Though the thyristor switched brake allows improved control over brake power dissipation, the brake power is still controlled in discrete power steps. The sampling rate of the controller determines the number of power steps. For example, the EMTP model uses a sampling rate of 400 microseconds. This allows variation in brake power in twenty discrete steps. Each step allows an approximately 70 MW change of power between cycles.

Another advantage in the use of thyristors to switch the brake is the turn-on speed of the device. Conventional circuit breakers require at least 2 cycles to switch on once the breaker trip coil receives a close from the controller. Thyristors can conduct current within one-half cycle of receiving a gate signal. This improved performance is modeled in the EMTP controller by reducing the ω_{max} parameter from 0.5 rad/sec to 0.2 rad/sec.

Two thyristor controllers, based on controller Con3, are tested. The first controller, labeled Con3*, uses a simplified thyristor model consisting of a controllable variable braking resistance. The second controller, labeled Con3, uses two thyristors, connected in anti-parallel, in each phase of the full braking resistor. Braking power is controlled by varying the firing angle.

The same faults are again applied in this testing, including an inner Northwest area fault between Chief Joseph and John Day (Fig. 5.20 and 5.21), an AC Intertie fault between John Day and Northern California (Fig. 5.22 and 5.23), and a 3rd AC Intertie Fault between John Day and Southern California (Fig. 5.24 and 5.25). The key performance indicators for the brake, as used in the three phase and single phase braking section, are observed for each of the faults. Appendix E shows the other generator relative velocities and additional relative angles. Each figure shows the effect of no brake control, and dynamic brake control with the third controller.

It is clear observing the relative velocity of the Northwest generator, in Figs. 20, 22, and 24, that full thyristor switched model, Con3, provides little or no system damping. Extensive tests show that increasing the firing angle to reduce brake power output severely distorts Chief Joseph 500 kV bus voltage. The addition of a brake power feedback loop in the controller improves, but does not correct, the condition.

This appears to be a limitation of the EMTP model, due to the limited transmission system connections at Chief Joseph.

The idealized controller Con3* provides excellent system damping through the three fault conditions. Figures 21, 23, and 25 illustrate the ability of the brake controller to reduce the rotor swing angle between the Northwest and Southern California generators. These figures also show again how a long duration reduced power second brake application significantly reduces the generator swing angle between Chief Joseph and Southern California generators.

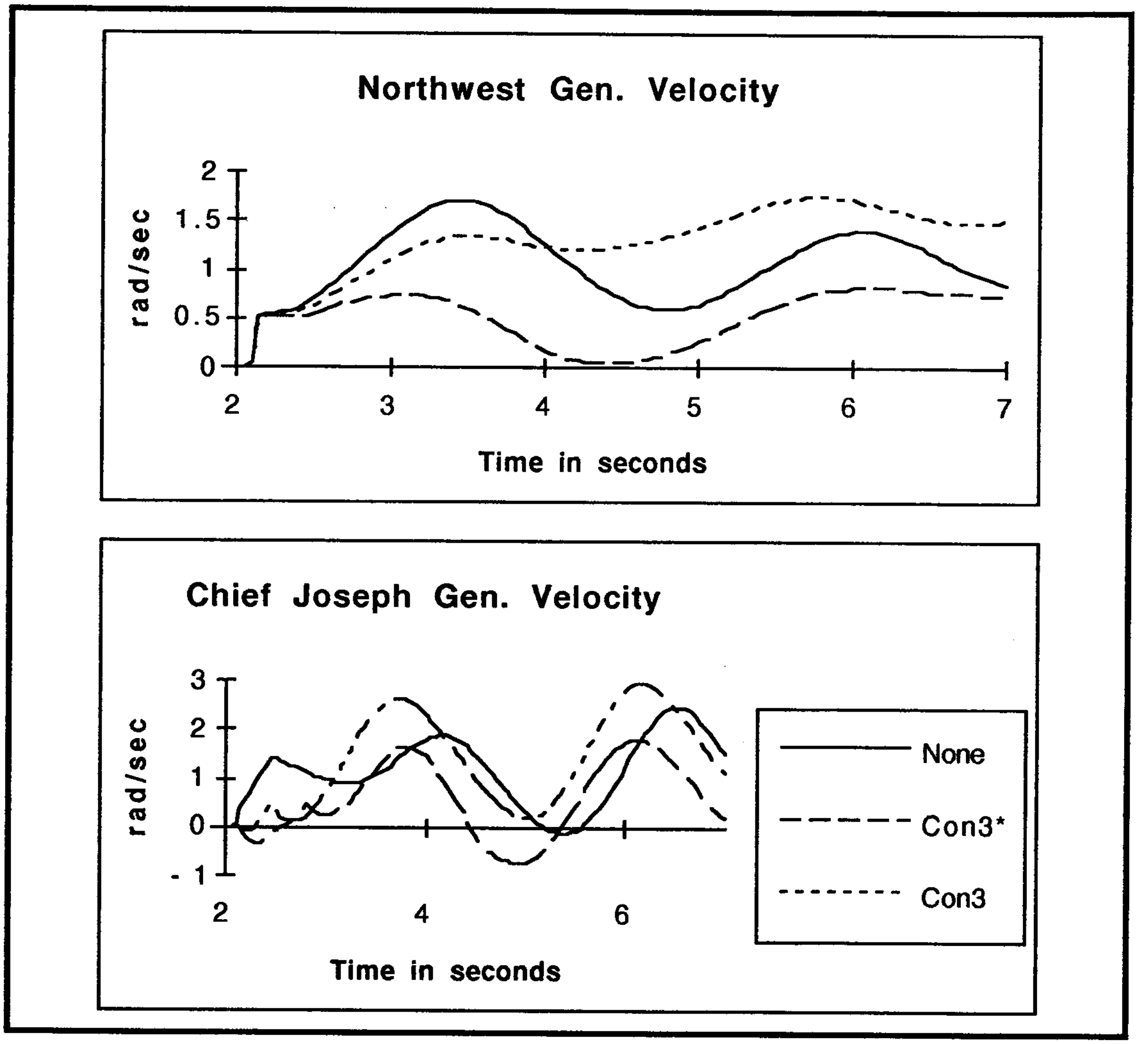

Figure 5.20 Relative Generator Velocities for John Day-Chief Joseph Fault

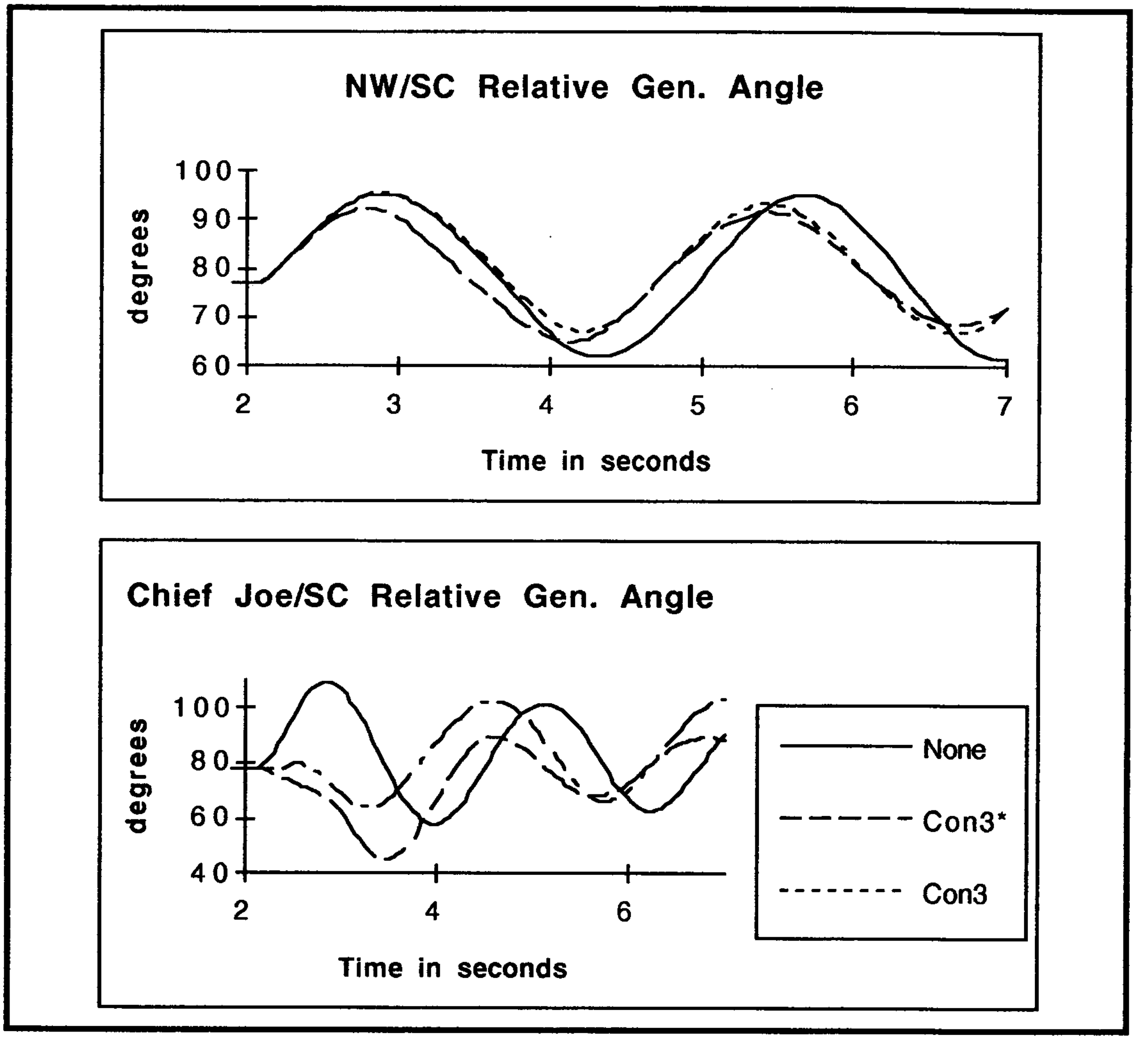

Figure 5.21 Relative Generator Swing Angles for John Day-Chief Joseph Fault

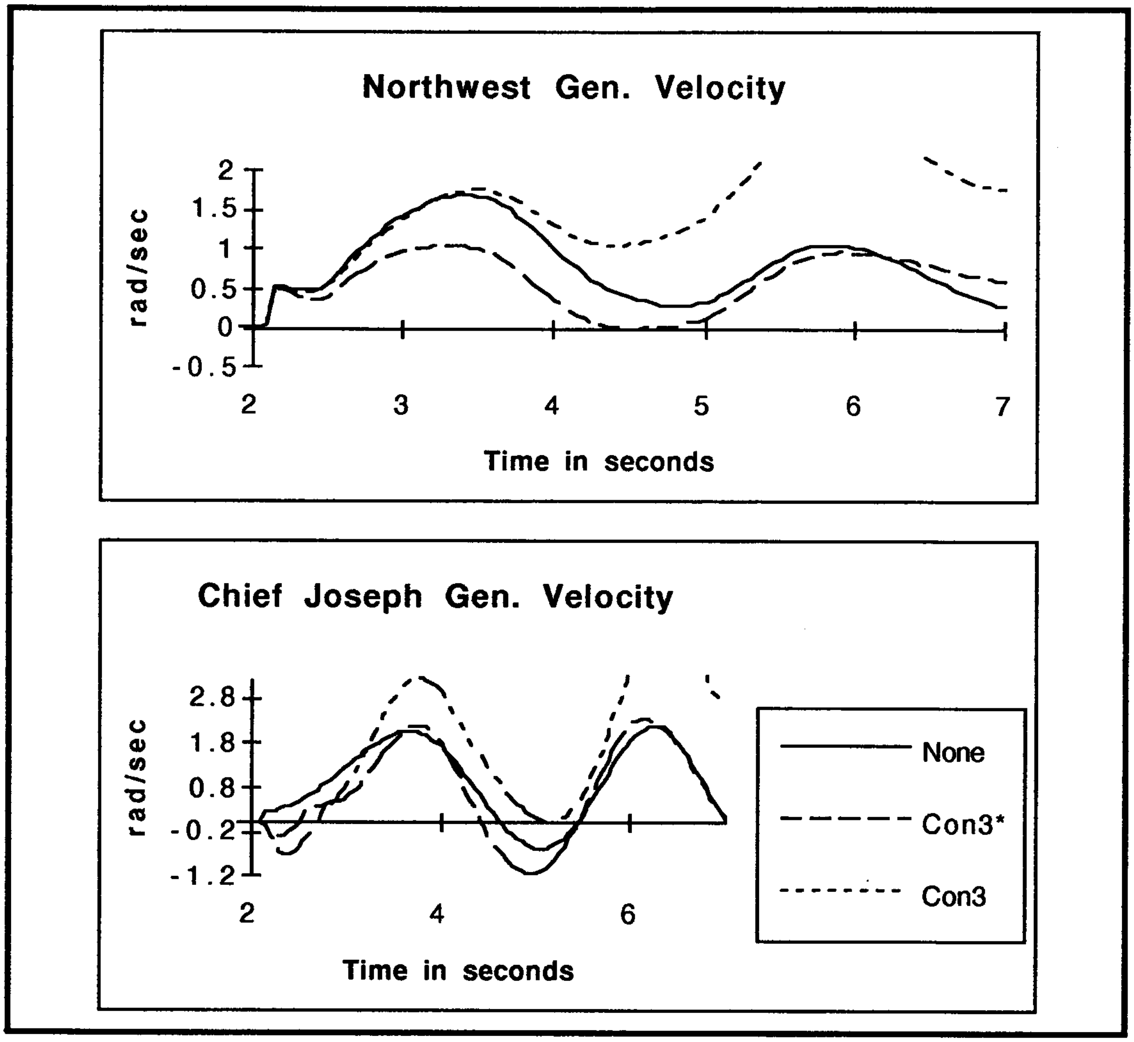

Figure 5.22 Relative Generator Velocities for John Day-Northern California AC Intertie Fault

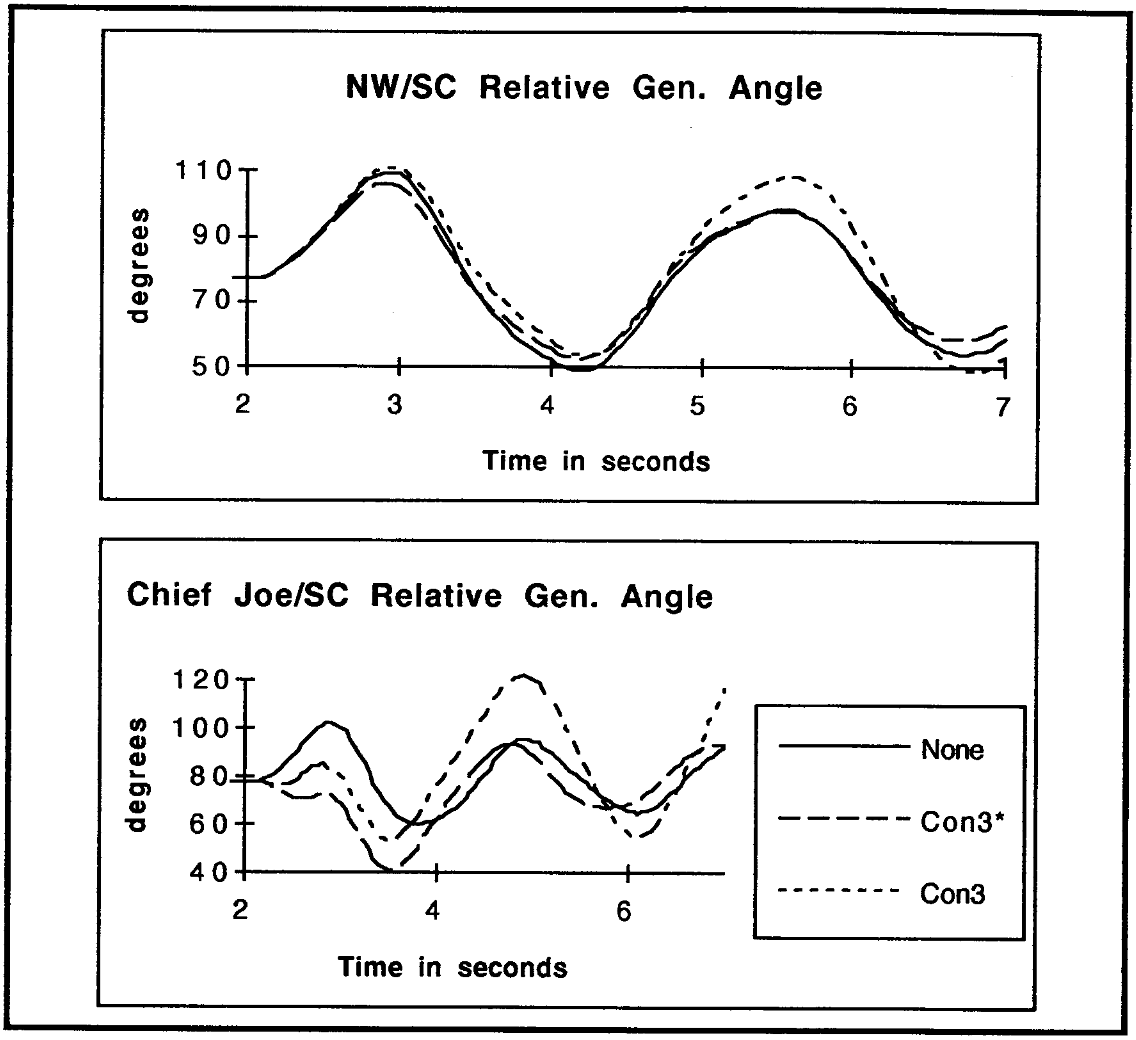

Figure 5.23 Relative Generator Swing Angles for John Day-Northern California AC Intertie Fault

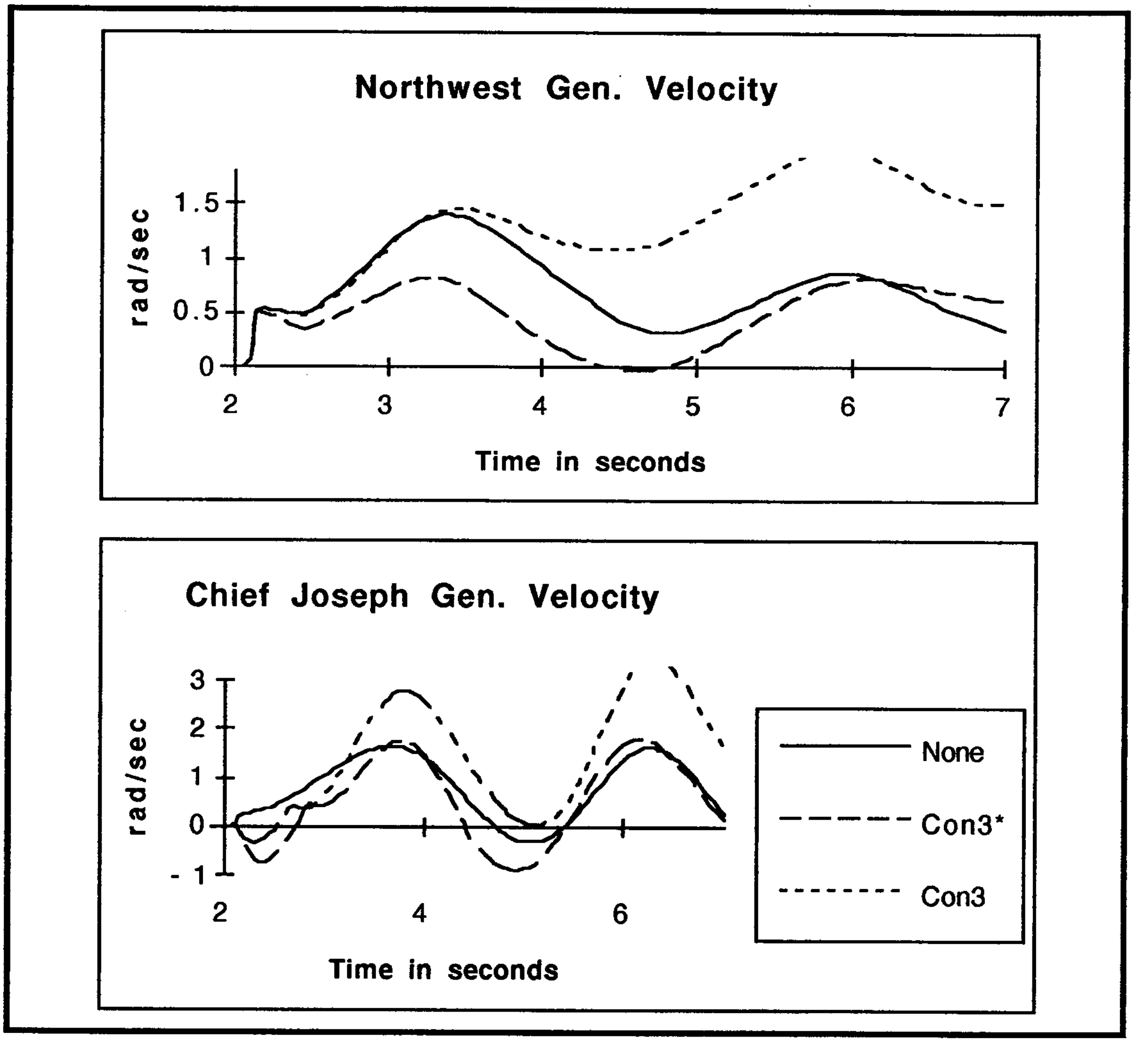

Figure 5.24 Relative Generator Velocities for John Day-Southern California 3rd AC Intertie Fault

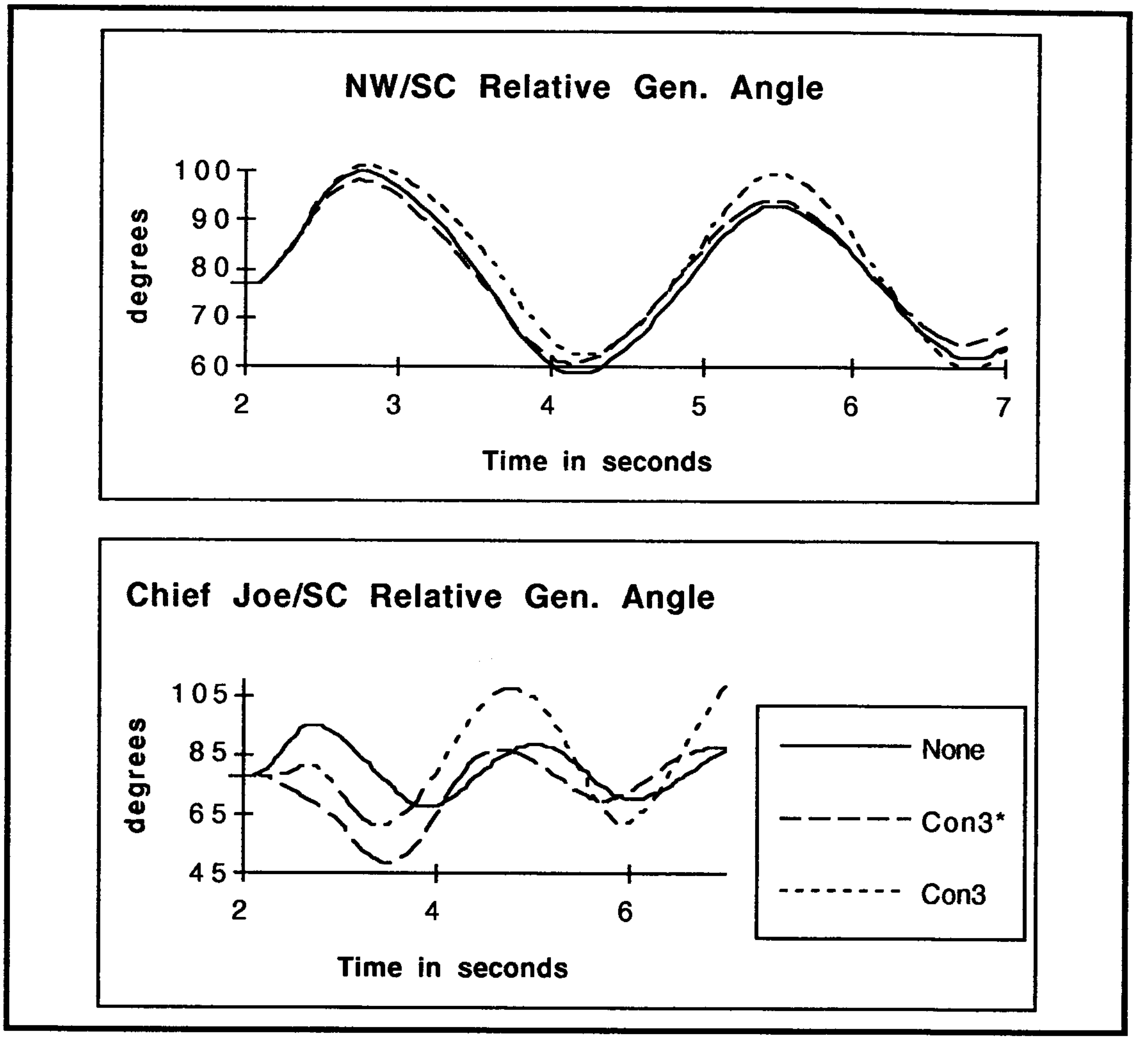

Figure 5.25 Relative Generator Swing Angles for John Day-
Southern California 3rd AC Intertie Fault

5.6. Comparison

The dynamic brakes primary purpose is to provide damping torque to maintain angular stability during the first swing following a major power system disturbance. The effectiveness of the braking control algorithms is evaluated using the relative velocity of the Northwest generator. The Northwest relative velocity is directly related to the energy stored in the Northwest generators' inertia due to the fault. The braking scheme that reduces the peak Northwest relative velocity best provides the most damping torque to the Northwest power system. Table 5.3 illustrates this concept for each of the braking control algorithms.

	Fault Location					
	John Day - Chief Jospeh		John Day - Northern California		John Day - Southern California	
Braking Control	Peak Relative Velocity in rad/sec	Reduction in 1st Swing Velocity	Peak Relative Velocity in rad/sec	Reduction in 1st Swing Velocity	Peak Relative Velocity in rad/sec	Reduction in 1st Swing Velocity
no braking	1.711	0.00%	1.693	0.00%	1.404	0.00%
3ø switching						
Con1	1.100	35.72%	1.362	19.55%	1.111	20.87%
Con2	0.945	44.75%	1.238	26.87%	0.988	29.63%
1ø switching						
Con1	0.837	51.07%	1.393	17.74%	1.136	19.10%
Con2	0.792	53.74%	1.191	29.65%	0.943	32.80%
Con3	0.779	54.46%	1.106	34.66%	0.874	37.77%
thyristor switching						
Con3*	0.742	56.61%	1.044	38.37%	0.816	41.85%
Con3	1.351	21.07%	1.768	-4.39%	1.466	-4.46%

Table 5.3 Peak First Swing Northwest Generator Relative Velocities

Controller Con3* provides the most reduction in peak relative velocity at the Northwest generator for all three faults. The problems with the thyristor switched brake model, controller Con3, are evident in the poor or negative damping provided in the three fault conditions. Comparing the percentage reduction, in first swing relative velocity, among the three faults, it is clear that dynamic braking is more effective the closer the fault is to the brake location. With this in mind, the brake controllers do provide improved damping for all three faults. Chapter 7 contains further comparison of switching methods and controllers.

CHAPTER 6 EXPERIMENTAL VERIFICATION OF DYNAMIC BRAKING

6.1. Introduction

Most design work for Flexible AC Transmission Systems (FACTS) is accomplished using computer modeling. This is a valuable tool, but there are many practical concerns and control implementations that are more effectively investigated with a physical system model. For this thesis, it was determined valuable to compare the results obtained from EMTP modeling with those obtained from a laboratory system model, as a means of verification.

6.2. System Hardware Design

6.2.1. Overview

Figure 6.1 shows an overview of the system model in block diagram form. The system is complex with many details involved in the design of each segment of the overall model. This laboratory model uses existing components, when available, to simplify the design and construction process. The system uses a personal computer (PC) based microprocessor controller connected to the thyristor gate driver circuit through a data acquisition card. The control system uses the transmission line power as an input to the microprocessor controller. A fiber optic link between the receiver and the microprocessor controller provides isolation of the input signal. Isolation of the synchronization voltage is provide by three small isolation transformers. The microprocessor controller produces an output voltage that the gate driver circuit uses to adjust the firing angle of the thyristors.

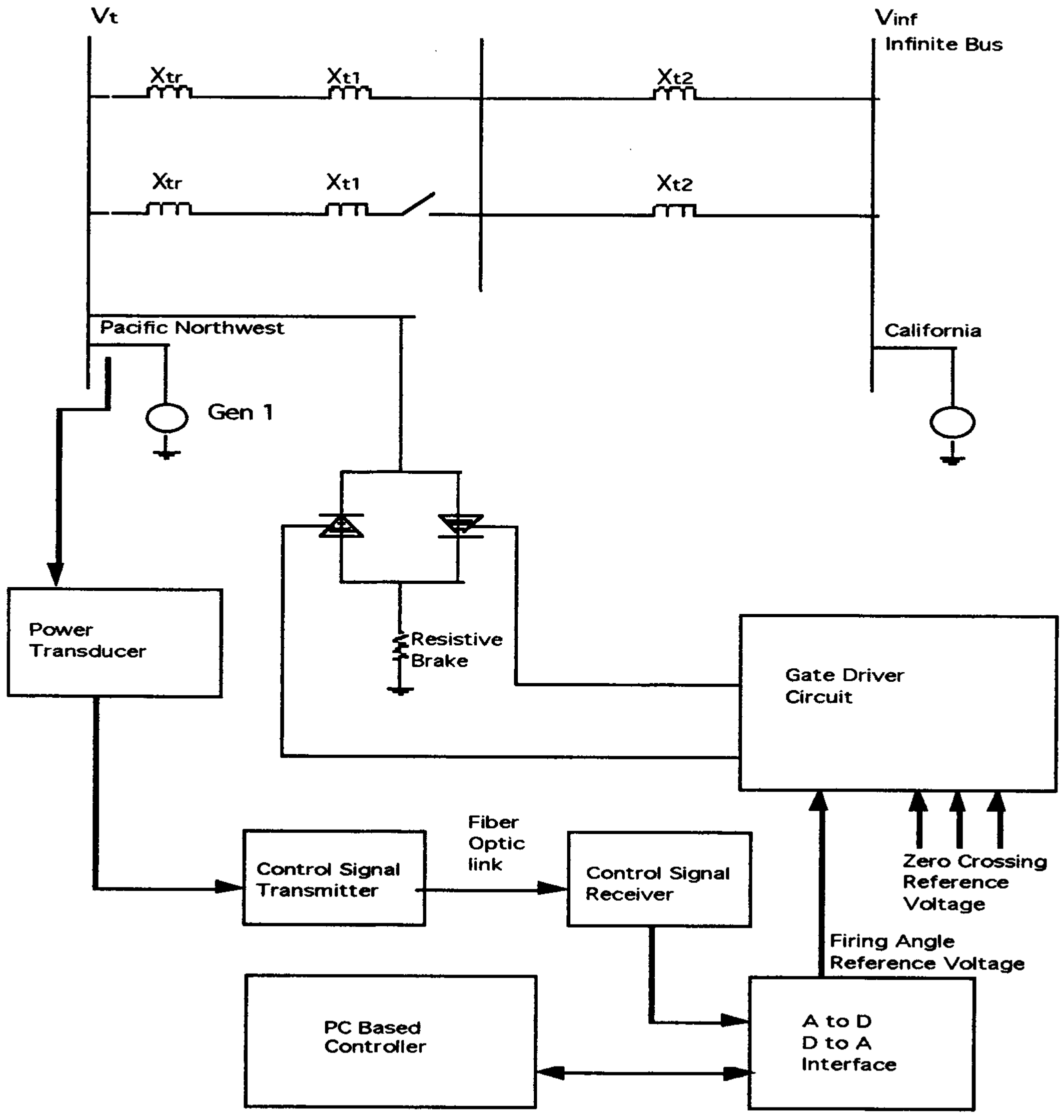

Figure 6.1 Single Line Diagram of Laboratory Model

6.2.2. Power System Model

The single machine infinite bus model is derived from a simple power system model that represents the transmission of power from the Northwest to California. An equivalent generator represents the Northwest generation. An infinite bus represents the California power system. The initial "real world" model is per unitized. A reasonable base value of voltage and apparent power is used to obtain parameters for the laboratory model. A base voltage of 230 volts and a base apparent power of 250 VA produces a reasonable model. Table 6.1 lists the selected model parameters. Figure 6.2 illustrates the power system components of the laboratory model.

SMIB Laboratory Model Parameters	
Vt = 236. 6 Volts	(line to line voltage rms)
Vinf = 230 Volts	(line to line voltage rms)
P3phasebrake = 3500 Watts	(maximum average brake power)
P3phasetrans = 6678 Watts	(total average transmission power)
Iphasebrake = 8. 92 Amps	(maximum rms brake phase current)
Rbrake = 14. 6 ohms	
Xt = 5.76 Ohms	
Xtr = 0. 24 Ohms	

Table 6.1 Single Machine Infinite Bus Laboratory Model Parameters

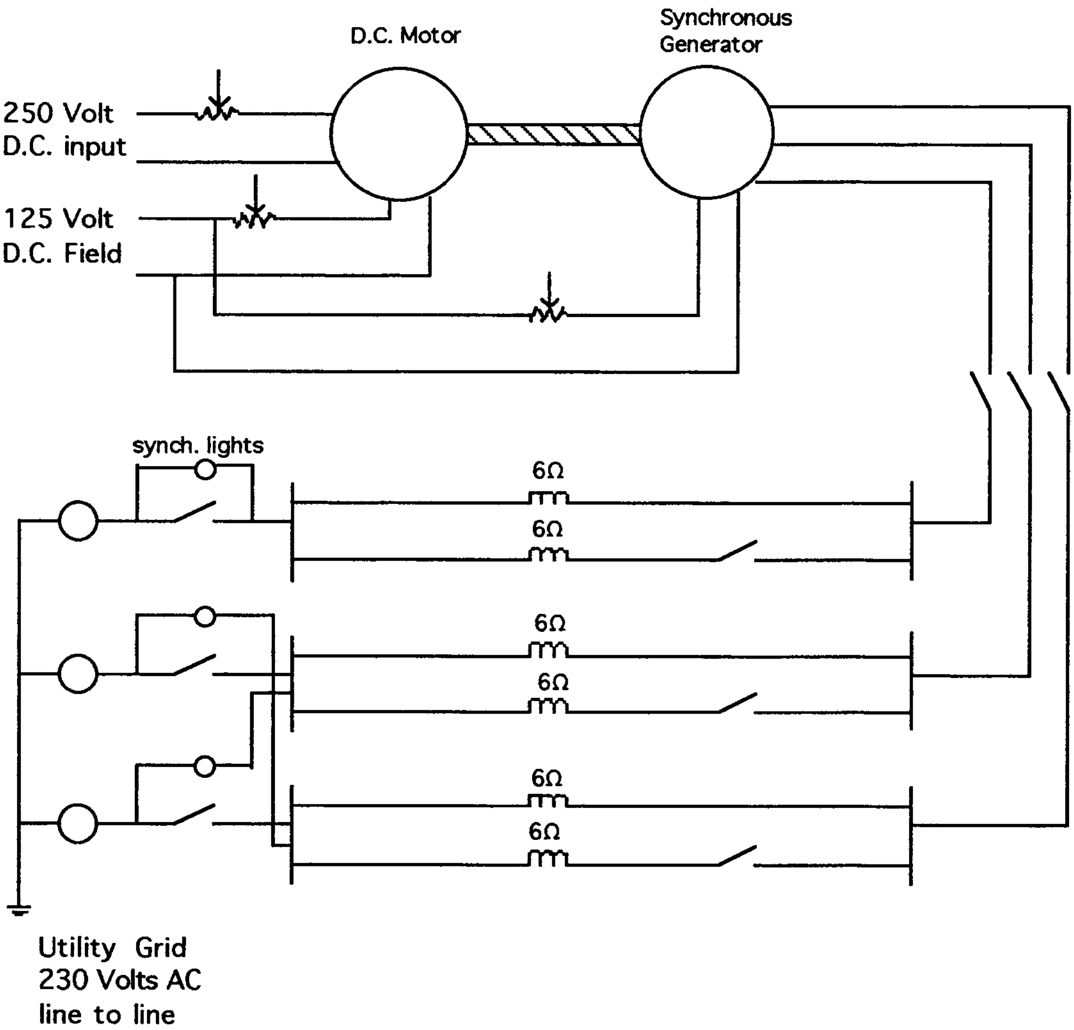

Figure 6.2 Power System Three Phase Schematic

6.2.3. Power Electronic Design

Constructing and operating this model provides practical understanding of power electronic system design. Power electronic design requires a broad understanding of power systems, circuit theory, control theory, thermal dynamics, and semiconductor devices. Figure 6.3 illustrates the resistive braking components including thyristors, gate driver circuit, zero crossing reference voltage, and snubbers.

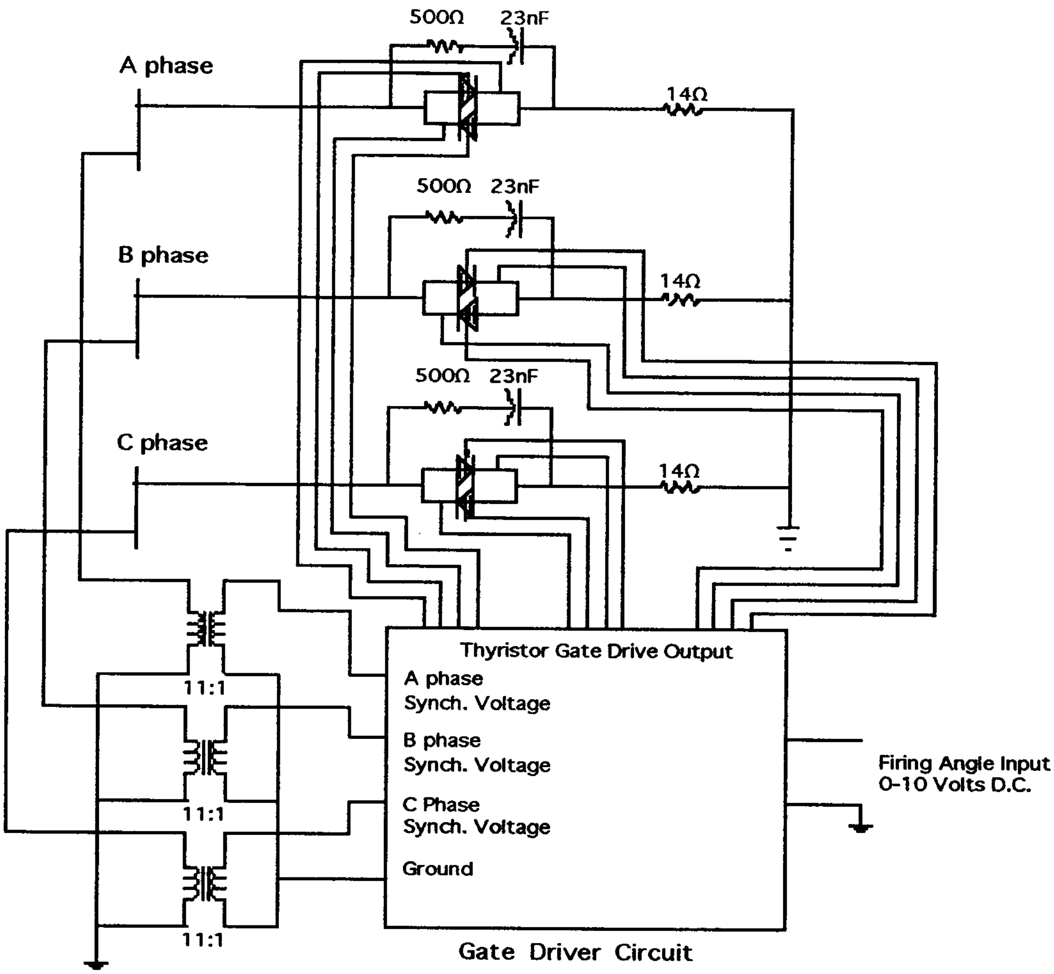

Figure 6.3 Three Phase Schematic of Thyristor Switched Braking Resistor

The thyristors chosen for this project are an International Rectifier module that incorporates two anti-parallel thyristors in one package. These modules have a voltage rating of 800 volts, a current rating of 55 amps rms, and a junction to case thermal resistance of 0. 137°C/W. Thus, device ratings exceed project requirements, which gives some flexibility in the design of both the heat sink and the snubber circuit. It also provides some safety margin for laboratory experimentation.

One important aspect in power electronic design is in the thermal dissipation requirements of the semiconductor devices. If the device can not properly dissipate the heat, produced by switching and conduction loss, there is the possibility of a thermal failure. Using heat sinks to reduce the thermal resistance between the semiconductor device and air is the most effective method to prevent thermal failure. Normal design procedure involves determining device thermal losses and ambient temperature during normal operation. This is used to calculate the heat sink thermal resistance required to dissipate this conservative device thermal loss estimate. It is determined that a heat sink for each module with a thermal resistance value around 1. 0°C/W would be acceptable, and give a little flexibility in our assumptions.

Another important aspect of power electronic design is in designing the snubber circuit for the device. With thyristors the concern is with device turn-off. The reverse recovery current can produce a large over-voltage across the device due to series inductance in the circuit. The snubber is designed to limit this over-voltage to a reasonable level. A simple R-C snubber works satisfactorily for this application. In the test circuit, series inductance is due mainly to the transformer connecting the circuit to the utility power grid. An estimated value of 5% proved to be sufficient. Snubber calculations indicate a 23 nF capacitor in series with a 500 Ω resistor would provide good protection for the thyristors. [12] The power dissipated in the snubber, during thyristor switching, is calculated to be 3.7 mW.

The thyristor gate driver circuit, used in this model, is a university developed circuit for use in many power electronic switching applications. [13] This circuit generates the gate pulses that drive the six thyristors in the model. Figure 6.3 shows the circuit inputs of a control voltage and three phase reference voltages. The control voltage is a 0 to 10 volt DC supplied by the microprocessor controller through an analog to digital converter. This voltage adjusts the firing angle of the gate pulse for each thyristor. The relationship between brake power output and reference voltage input is expressed in equation 6.1. Figure 6.4 further illustrates this relationship.

$$Pbrake = 3500 \cdot \cos\left(\frac{\pi \cdot Vref}{14}\right) \tag{6.1}$$

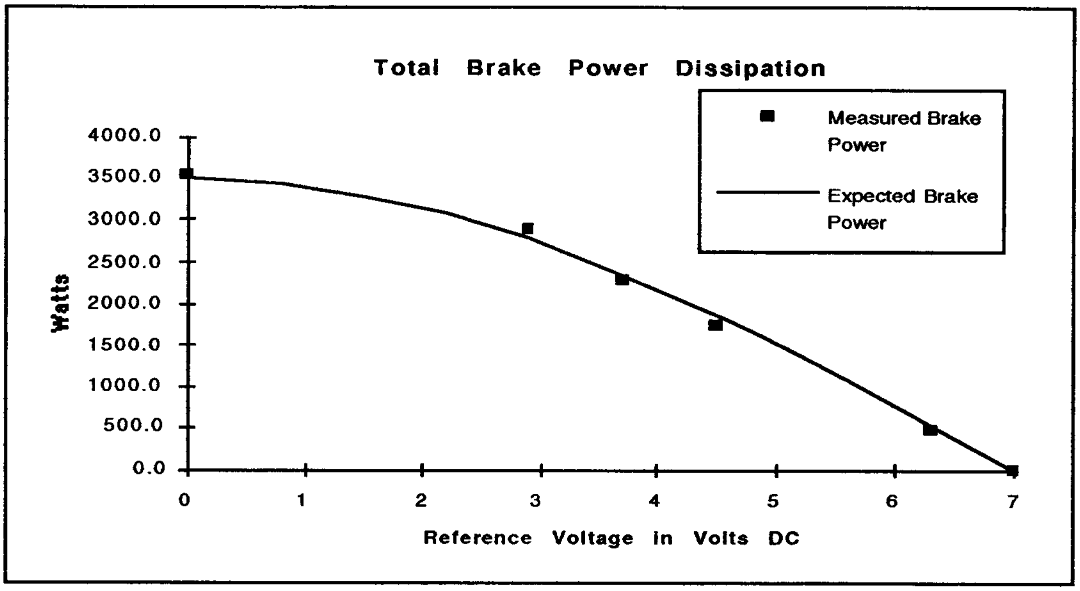

Figure 6.4 Brake Power vs. Control Voltage

As illustrated in Fig. 6.3, voltages are measured at the terminals of the thyristors and connected through transformers to the gate driver circuit. The transformers provide two functions. They step down the voltages from the 230 volts line to line voltages to a more desirable level, and provide voltage isolation. The gate driver circuit uses these voltages to determine the zero crossings of each phase voltage. This allows proper synchronization of the gate pulses, determined by firing angle, for each thyristor. The connection between the gate driver circuit and the thyristor gate terminals is also transformer isolated.

6.2.4. Input Measurement

The power system parameter used by the microcontroller is generator output power. Measuring this parameter allows calculation of approximate generator mechanical frequency. A three phase power transducer measures power at the terminals of the generator. The transducer outputs a 0 to 10 volt DC signal to a 12-bit analog to digital converter. The sending circuit converts this parallel digital signal to a serial signal and sends it through a fiber optic link to a receiving unit. The fiber-optic cable provides additional isolation between the 230 volt generator output and the microprocessor controller. The receiving unit converts the serial digital power measurement back into a parallel signal for connection to the PC microcontroller.

6.3. Control System Software Design

The development of software for the control system is accomplished on the PC based microcontroller using assembly language programming. The controller uses generator output power as input, and determines a 0 to 10 volt DC voltage that determines the firing angle for the gate driver circuit. A control system program is developed to simulate full variable braking power thyristor switching. This control algorithm is the same as Con3 in Fig. 5.13, accept that in the laboratory model there is only one generator in the system. Appendix B provides the complete assembly language controller code.

6.4. Experimental Results

The laboratory model is tested by subsections to verify operation of the complete system. In testing the thyristor braking resistor, a 230 volt line to line utility source is applied to the terminals of the thyristors. Voltage, current and power are measured on each phase of the brake at different firing angles. Figure 6.4 shows points measured in these laboratory tests, and Figs. 6.5 and 6.6 illustrate voltage waveforms measured across one phase of the braking resistor at different firing angles. These figures show how the firing angle determines the place in a voltage cycle where the thyristor goes into conduction. In this model the phases of the braking resistor are connected in an ungrounded wye configuration as illustrated in Fig. 6.3. When a thyristor in one phase conducts, the current must flow through one of the remaining phases to complete a current path. This is illustrated by the multiple peaks on the voltage waveforms in Figs. 6.5 and 6.6.

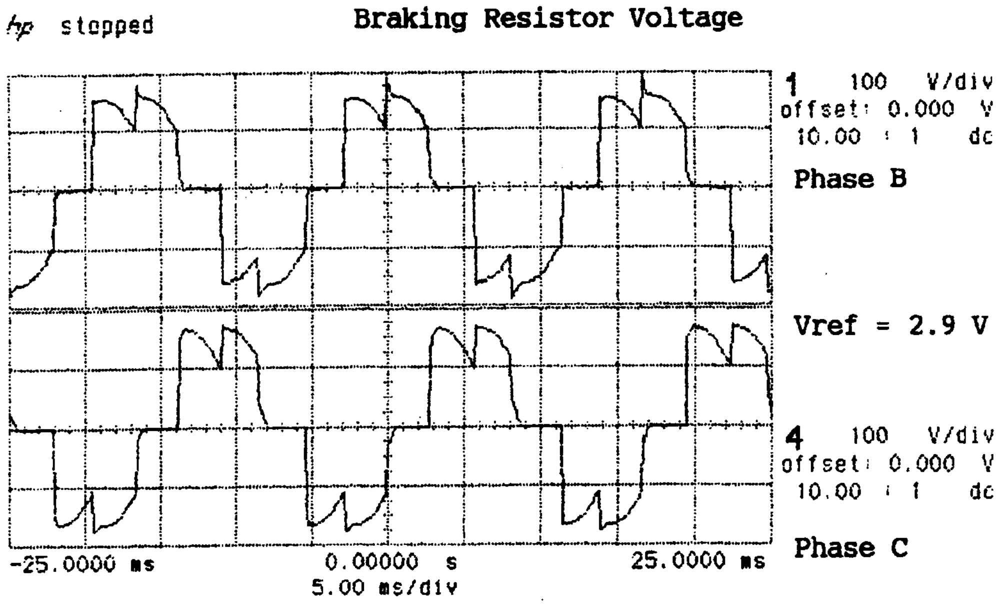

Figure 6.5 Laboratory Tests of Braking Resistor Voltage at a 75° Firing Angle

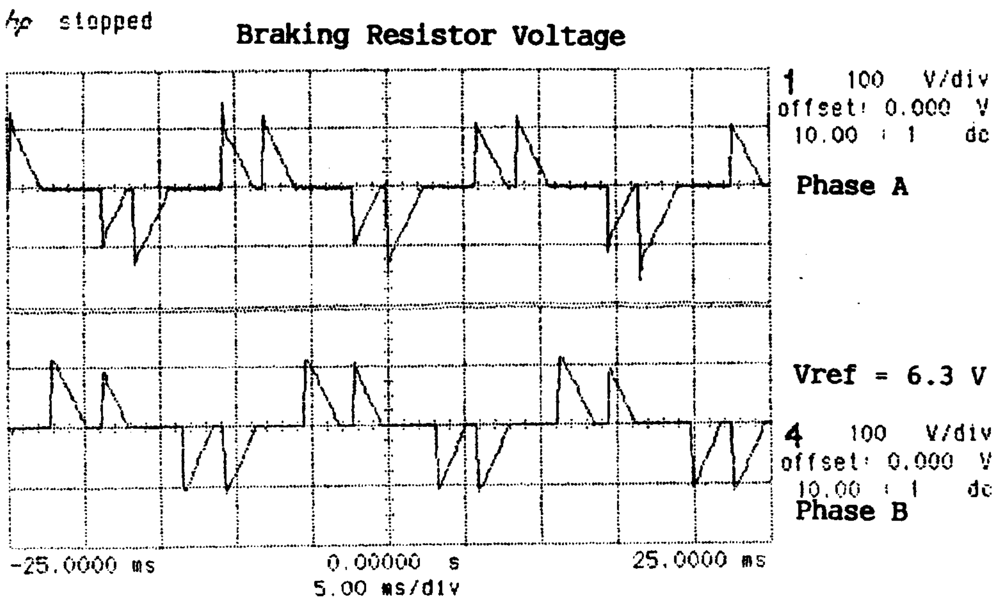

Figure 6.6 Laboratory Tests of Braking Resistor Voltage at a 160° Firing Angle

The dynamic performance of the complete laboratory SMIB model is evaluated. The generator is first synchronized to the utility power grid. Power output from the DC motor prime mover is increased until approximately 6 kW is generated and transferred across the two parallel transmission lines. The model contains a three-pole switch in one of the parallel transmission lines as shown in Figs. 6.1 and 6.2. A disturbance is introduced to the power system by opening and subsequently reclosing this switch. The disturbance momentarily blocks the steady-state flow of power through one of the transmission lines. The rotor velocity increases as the inertia of the generator's rotor stores this excess energy and upon reclosure, the generator rotor angle swings against the infinite bus provided by the utility grid until damping returns the system to steady state. Disturbances investigated are not large enough to cause generator instability.

The oscillation of the synchronous generator is observed by plotting the total generator power output, as measured through a three phase power transducer, on a digital oscilloscope. Accelerating power is interpreted from the oscilloscope plot due to the oscillation about a fixed mechanical power transfer level. Equation 3.1 shows the relationship between the accelerating power and generator velocity. Figure 6.7 illustrates the oscillations of the generator without dynamic braking control. The maximum amplitude of the accelerating power oscillation is approximately 4.7 kW.

To investigate performance of the dynamic brake, the brake control unit is activated and a similar disturbance is again applied to the power system model. Figure 6.8 shows the generator power output of the controlled system. The maximum amplitude of the accelerating power oscillation, with dynamic braking, is approximately 2.8 kW.

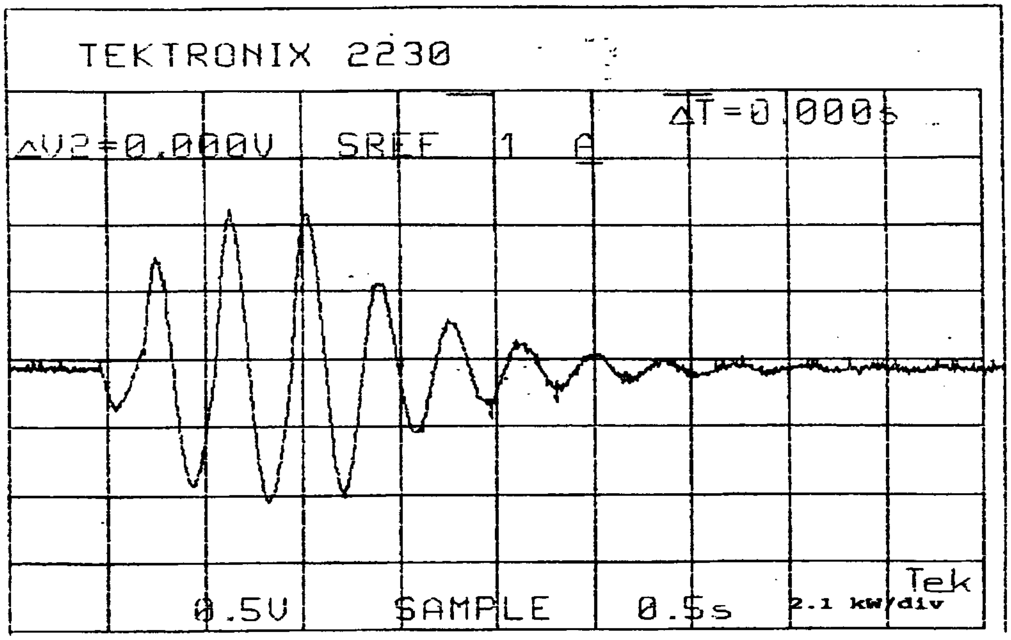

Figure 6.7 Generator Power Output without Dynamic Brake Control

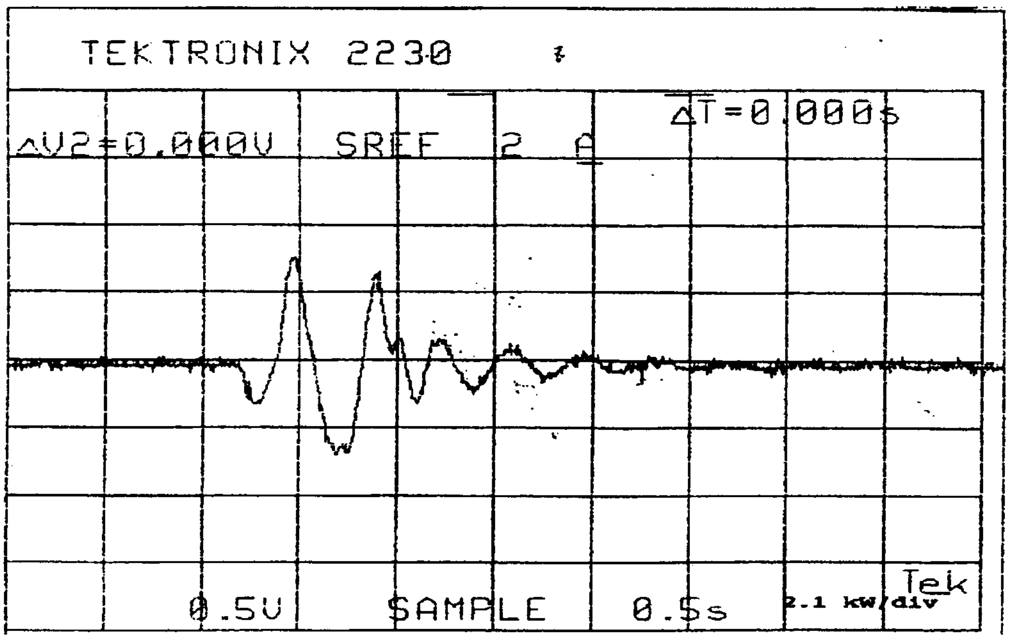

Figure 6.8 Generator Power Output with Dynamic Brake Control

6.5. Conclusion

The hands-on experience gained in working with a physical laboratory model proves to be a valuable experience. The engineering design problems described in this chapter are representative of those encountered in full scale FACTS design. Many of these issues are overlooked in most computer simulations of FACTS in a power system model.

One lesson learned through the failure of an isolation transformer on the gate driver circuit is the importance of electrical isolation in power electronic design. This failure in isolation between the thyristor gate and the control circuitry allows 230 volts to be applied across low voltage control circuits. This fault damaged a hard disk drive controller in the PC, the digital to analog converter, and the gate driver circuit. It is of paramount importance to have proper isolation in power electronic circuits between the higher voltages and the control circuit. Most applications of thyristors in power systems require thyristors that are pulsed optically, through a fiber-optic cable, to begin conduction. Optical isolation provides the best protection available.

The brake controller operates successfully and reduces the amplitude of the accelerating power oscillation by 40%. This improved damping of the transient response to the power system disturbance can also be detected audibly in the sound of the generator oscillation and visually with a strobe light on the generator shaft. Chapter 7 compares the laboratory model performance with an equivalent 5-generator EMTP model fault case.

CHAPTER 7 COMPARISON OF SWITCHING METHODS

7.1. Comparison of Computer Simulation and Laboratory Models

Chapter 6 discussed the design, construction, and operation of a laboratory power system model that contains a thyristor switched dynamic brake. Working with this model provides practical experience necessary in the construction of a full scale thyristor switched dynamic brake. It also validates the overall performance of the proposed thyristor controller in a laboratory environment.

Though the laboratory model contains only a single generator, and the EMTP model contains 5 generators, some generalizations are made in comparing the performance of the two models. The laboratory model represents the inter-area power flow between the Northwest and California. The John Day-Northern California fault in the 5-Generator EMTP model compares with the disturbance placed on the laboratory power system model. In the laboratory the generator power measurement, illustrated in Figs. 6.7 and 6.8, is the primary measurement of the dynamic braking performance. For the EMTP model the primary measurement is the Northwest generator relative velocity, illustrated in Fig. 5.20. There is a 90 degree phase shift between these two measurements, but the relative magnitude of the reduction in generator swing is compared. The thyristor switched EMTP model using Con3* braking control shows a 38% reduction in peak relative velocity for the described disturbance. This compares reasonably with the 40% reduction in peak accelerating power observed with the laboratory model. These results confirm that the dynamic braking controllers, analyzed using the EMTP models, are realizable in a physical system.

7.2. Control Algorithm Performance

The EMTP 5-generator model studies, discussed in chapter 6, provide a strong basis for evaluation of the performance of the control methods described in chapter 3. Initial fault studies investigated the effects of the 3 phase faults listed in table 5.1. By studying the effects of fixed duration braking on the listed faults, it became clear for which faults dynamic braking improved system stability. The three faults selected for the studies in chapter 5 are faults that require dynamic braking to maintain transient stability. These faults are representative of those Western power system faults that either occur in the Northwest near the Chief Joseph brake, or occur along the Pacific interties with California.

The initial fault studies demonstrate the importance of keeping the generators at Chief Joseph from separating from the rest of the power system during brake application. A shorter duration brake application provides maximum reduction of the first swing and maintains synchronism between Chief Joseph and the rest of the power system. The logic of the controllers incorporates this concept by removing the brake, in the first application, once Chief Joseph relative velocity goes below a minimum level. This method proves successful in damping the first swing and preventing Chief Joseph separation in all cases.

Another performance criterion for dynamic brake control is the ability of a controller to provide optimal first swing damping for different power system disturbances. This is accomplished in two ways. First, each of the controllers investigated uses the Chief Joseph and Northwest generators relative velocities to determine brake application duration. The brake dissipates more energy for disturbances that store larger amounts of energy in the Northwest generators' inertia.

Second, the controller Con3 can vary the brake power applied either with single phase switching or thyristor switching. This controller uses the maximum value of accelerating power during a disturbance to determine the initial brake power application. Table 5.3 displays the peak relative velocity of the Northwest generator with all braking controllers. Comparing the performance percentages of the John Day-Chief Joseph fault with the other two faults shows that the brake is more effective the closer the disturbance is to the dynamic brake. A good measure of the generality of these controllers is the comparison of the John Day-Northern California fault and the John Day-Southern California results. Both of these faults, in electrical terms, are the same distance from the dynamic brake. The John Day-Northern California fault interrupts the flow of approximately 1500 MW of power to California, while the John Day-Southern California fault interrupts approximately 800 MW. (See Figure 5.1) The braking performance percentages of both faults are relatively equal for each controller. This confirms the flexibility of the different controllers to provide optimal first swing damping for different disturbance severity.

As expected, the performance of the different controllers and switching methods is directly related to complexity of the dynamic braking system. Controller Con3* with the variable power braking resistor, obtained with a thyristor switching model, implemented with a controlled variable braking resistance, achieves maximum damping of the Northwest generator first swing relative velocity. A close second in performance is the use controller Con3 with single phase circuit breaker switching of the brake. Unfortunately the full thyristor implemented braking model, using controller Con3, has poor performance in comparison to all other switching methods. This is illustrated in table 5.3. This degradation in performance is attributed to distortion of the sinusoidal voltage waveforms at Chief Joseph bus D, where the braking resistor is connected. This distortion causes difficulties in achieving the controller commanded brake power output, even with a brake power feedback loop in place. The brake power output commanded by the brake controller is In the actual power system there are more transmission connections at Chief Joseph than modeled in the 5-generator EMTP models. This is a limitation of these simple EMTP power system models. In practice the thyristor switched braking resistor should cause significantly less distortion to the 500 kV and 230 kV bus voltages at Chief Joseph resulting in performance close to that realized with controller Con3* and the idealized thyristor switched resistive braking model.

Inserting of the braking resistor twice during the first swing proves to be an effective switching technique. Controller Con2 achieves an approximately 9% increase in performance over controller Con1 for each of the faults. This increased performance is attributed to the long duration of the second brake insertion. The brake controller limits the first brake duration to keep the Chief Joseph generator from separating. At the point of the second brake insertion, the swing of the Northwest generator is strong enough that the Chief Joseph generator will not separate if a reduced brake power is used. This allows for a longer duration brake insertion and hence the dissipation of more energy from the power system.

7.3. Practical Feasibility

In evaluating these switching methods, several practical concerns are identified for the various control algorithms. One concern is with the calculation of generator relative velocity from generator accelerating power measurements. A few seconds after the beginning of a disturbance, the value of calculated relative velocity begins to deviate slightly from the actual relative velocity. This is due to the assumption that ω_0, steady state electrical frequency, is constant throughout a disturbance. In a physical dynamic brake control system, the controller needs to eliminate this error for continuous accurate measurement of relative velocity through multiple disturbances.

Another concern is the introduction of harmonics with thyristor switching of the brake. Changing the firing angle of the thyristors varies the average voltage across the braking resistor over one cycle. This changes brake power output. Applying the brake with firing angles greater than zero introduces harmonics into the power system due to the non-sinusoidal brake current. Due to the large size of the brake, thyristor switching also distorts the 500 kV bus voltage at Chief Joseph. For this reason the thyristor switched controller requires a feedback loop of brake power, to correct for discrepancies between controller required and measured brake power output. This adds to the complexity of the thyristor switched system. More detailed computer simulation studies are necessary to determine to what extent thyristor switching of the brake will distort 500 kV and 230 kV bus voltages at Chief Joseph.

It is clear that as the dynamic brake evolves from three phase breaker switching to single phase breaker switching and to thyristor switching, the system becomes more complex. A more complex system usually requires more maintenance time and has more failures than a less complex system. In comparing these switching methods it is important to evaluate the ratio of performance to complexity. At this time, the increased performance justifies the added complexity involved in going to single phase breaker switching. A change to thyristor switching is a large increase in complexity over the single phase breaker switched system. Thyristor switching of the dynamic brake would require many subsystems currently not included in the brake system. Examples of these subsystems include thyristor gate driver circuitry and thyristor cooling systems. The performance to complexity ratio for this case is much less than single phase switching. This system complexity will decrease with increased use of FACTS devices in the power system.

7.4. Preliminary Cost Evaluation

Another factor that should be taken into account in comparing methods is the cost. Current industry prices for shunt connected thyristor switched devices are in the \$25 - \$30/kVA. This indicates the cost of adding thyristor switching to the complete 1400 MW Chief Joseph brake is approximately \$30 - \$40 million. This price includes installation. The cost of replacing a three-pole vacuum circuit breaker with three single-pole vacuum circuit breakers is approximately \$500,000. This is a considerably more practical expenditure for the increased performance.

Currently thyristors are not cost effective for a brake the size of Chief Joseph. Future brake sites at lower brake power levels may justify the use of thyristor switched dynamic braking. As power electronics becomes more prevalent in the power system the cost of the devices will continue to decrease. At some time in the future the cost per kVA will decrease to an acceptable level.

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

8.1. Result Highlights

There are many accomplishments in this thesis work. A new understanding of the requirements of dynamic braking in the Western power system is gained. New control options for the Chief Joseph dynamic brake are developed and evaluated using both EMTP computer simulation and a laboratory model.

An important issue in the design of a power system controller is the location and type of controller inputs. It is currently not possible to have all desired inputs available for a controller. A novel approach is developed that uses computer simulated accelerating power measurements at generation sites throughout the Northwest to determine a Northwest equivalent generator average system response to several faults. This approach compares the response of individual generators against the average system to determine which generator locations follow the system average most closely. Results show that the current input locations of Chief Joseph and John Day may not provide complete coverage for all system faults for both light and heavy loading conditions. Using Chief Joseph and one or two input locations listed near the top of table 4.4 provides inputs that represent well the average Northwest power system response.

A SMIB laboratory model with a thyristor switched braking resistor is designed, constructed, and tested. This model allows a better understanding of the practical aspects of the design of a thyristor switched brake. Operation of the laboratory model provides verification that the proposed control system actually works in a physical model.

Three different control systems are evaluated using the three methods of brake switching. There was some initial concern that single-phase switching of the brake would introduce levels of zero and negative sequence currents that would trip line relaying. Studies with the 5-generator EMTP model indicate that the level of zero and negative sequence currents is small enough to be still considered a practical switching option. The use of single-phase switching of the brake, to allow varying of brake power in three steps, is evaluated using controller Con3. This system has the best performance to cost and performance to complexity ratios of the three tested switching methods.

The use of thyristors to switch the braking resistor does provide an increase in performance due to the faster switching and complete variable power control. At this time, and for the Chief Joseph braking resistor, the increased performance does not justify the additional system complexity, or the increased system costs. These EMTP model tests do indicate that a smaller size brake can provide close to or better performance than the full 1400 MW for the disturbances investigated. Table 5.3 illustrates this result by comparing controller Con1 and Con2 performance with single phase and three phase breaker switching. A 350 MW thyristor switched braking resistor, 1/4 the size of the Chief Joseph braking resistor, may provide the same performance of a larger circuit breaker switched brake. The cost per performance ratio of this new facility may make this device more realizable.

8.2. Possible Future Work

These studies have introduced many ideas for future work in power system braking and transient stability control. Many of these ideas are a natural continuation of this thesis work. An example is the need for further studies that investigate the effect of harmonics, introduced to the power system by thyristor switching of the brake. The brake design investigated in this thesis uses a thyristor valve in each phase of the brake. A possible solution to these harmonic problems is the use of a full converter, possibly using turn-off semiconductors such as gate turn-off thyristors (GTO) and MOS controlled thyristor (MCT). [20] This system would use a single braking resistor placed across the DC output of the converter. Proper converter control can allow extraction of braking power with little introduction of harmonics. [14]

One problem realized in these studies is the high cost of implementing thyristor switching of a shunt connected device. Many thyristors in series are needed to deal with the high switching voltage. One idea to reduce this cost is the development of a hybrid braking resistor switching technique. The combination of circuit breaker and thyristor switching in one brake installation may allow the reduction in thyristor rating to a cost effective level. Another possibility is the combination of a thyristor switched braking resistor, which only operates for extreme power system disturbances, with a static var compensator (SVC), which operates continually. This combination may justify the excessive cost of the thyristor switching.

Another logical extension of this research is in the replacement of the braking resistor with a super-conducting magnetic energy storage (SMES) system. Such a system could allow complete control of real and reactive power injection and removal at the point of connection. This system would not only be usefully for transient stability control, but also can provide load level support, and system stabilization control for mid-term, long-term, and voltage stability problems. [15]

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APPENDICES

Appendix A EMTP Model Code

Light Spring Model

```
C 1 AC INTERTIE FAULT AT JOHN DAY to chief Joe
C feedback brake controller
BEGIN NEW DATA CASE
$listoff
C deltat    tmax    xopt    copt   epsiln  tolmat  tstart
  0.0004    7.00    60.0
C iout      iplot   idoubl   kssout   maxout    ipun   memsav    icat
nenerg
     125     125       0       0        0       0       0        1
C THIS FILE IS FOR TESTING IN 5-MACHINE POWER SYSTEM
C ==========START 5-MACHINE PLANT CARDS===================
C          1           2           3           4           5           6
7
C
34567890123456789012345678901234567890123456789012345678901234567890
1234567890
C BUS   1BUS   2BUS   3BUS   4RRRRRRLLLLLLCCCCCC
  GEN2A D1A              0.001
  GEN2B D1B              0.001
  GEN2C D1C              0.001
  GEN1A BB1A             1.E-8
  GEN1B BB1B             1.E-8
  GEN1C BB1C             1.E-8
  GEN3A F1A              0.001
  GEN3B F1B              0.001
  GEN3C F1C              0.001
C ------Transformer cards----------------------------------
  TRANSFORMER                        TR1
            9999
 1BB1A                         .0001 13.8
 2BA                           1.1102500.0
  TRANSFORMER                        TR2
            9999
 1BB1B                         .0001 13.8
 2BB                           1.1102500.0
  TRANSFORMER                        TR3
            9999
 1BB1C                         .0001 13.8
 2BC                           1.1102500.0
  TRANSFORMER                        TR4
            9999
 1D1A                          .0001 13.8
 2DA                           33.5  500.0
  TRANSFORMER                        TR5
```

```
            9999
 1D1B                               .0001 13.8
 2DB                                33.5  500.0
  TRANSFORMER                             TR6
            9999
 1D1C                               .0001 13.8
 2DC                                33.5  500.0
  TRANSFORMER                             TR10
            9999
 1GEN4A                             .0001 13.8
 2IA                                1.696 500.0
  TRANSFORMER                             TR11
            9999
 1GEN4B                             .0001 13.8
 2IB                                1.696 500.0
  TRANSFORMER                             TR12
            9999
 1GEN4C                             .0001 13.8
 2IC                                1.696 500.0
  TRANSFORMER                             TR7
            9999
 1F1A                               .0001 25.0
 2FA                                8.333 500.0
  TRANSFORMER                             TR8
            9999
 1F1B                               .0001 25.0
 2FB                                8.333 500.0
  TRANSFORMER                             TR9
            9999
 1F1C                               .0001 25.0
 2FC                                8.333 500.0
  TRANSFORMER                             TR13
            9999
 1GEN5A                             .0001 25.0
 2HA                                9.866 500.0
  TRANSFORMER                             TR14
            9999
 1GEN5B                             .0001 25.0
 2HB                                9.866 500.0
  TRANSFORMER                             TR15
            9999
 1GEN5C                             .0001 25.0
 2HC                                9.866 500.0
C ----------------BRAKE MODEL--------------------------------
  B1A   B2A              1.0E8
  B1B   B2B              1.0E8
  B1C   B2C              1.0E8
  DA           B1A                                              0.001
1
  DB           B1B                                              0.001
1
  DC           B1C                                              0.001
1
```

```
  B2A          B3A                                                    206.36
4
  B2B          B3B                                                    206.36
4
  B2C          B3C                                                    206.36
4
  B3A                            0.0001
  B3B                            0.0001
  B3C                            0.0001
C -----------------Transmission line Parameters----------------
  BA     CA                      21.395
  BB     CB                      21.395
  BC     CC                      21.395
  DA     CA                       324.0
  DB     CB                       324.0
  DC     CC                       324.0
  L1A    L2A                      324.0
  L1B    L2B                      324.0
  L1C    L2C                      324.0
C ----------------- 3rd AC Intertie -------------------
  CA     IA                      267.45
  CB     IB                      267.45
  CC     IC                      267.45
C ----------------- 1st and 2nd AC Intertie -----------
  CA     FA                      119.16
  CB     FB                      119.16
  CC     FC                      119.16
  CA     FA                      119.16
  CB     FB                      119.16
  CC     FC                      119.16
  FA     IA                      47.000
  FB     IB                      47.000
  FC     IC                      47.000
C ----------------- Eastern Intertie ------------------
  HA     CA                       465.0
  HB     CB                       465.0
  HC     CC                       465.0
  HA     CA                       465.0
  HB     CB                       465.0
  HC     CC                       465.0
C ----------------- Shunt Compensation ----------------
  HA                             7170.0
  HB                             7170.0
  HC                             7170.0
  FA                                   10.90
  FB                                   10.90
  FC                                   10.90
  IA                                   13.55
  IB                                   13.55
  IC                                   13.55
  CA                                   34.30
  CB                                   34.30
  CC                                   34.30
  BA                                   26.21
```

```
  BB                                    26.21
  BC                                    26.21
  DA                                     2.63
  DB                                     2.63
  DC                                     2.63
C ---------------- Loads ----------------------------
  HA                       249.57
  HB                       249.57
  HC                       249.57
  BA                       11.628
  BB                       11.628
  BC                       11.628
  CA                       108.0
  CB                       108.0
  CC                       108.0
  FA                       43.48
  FB                       43.48
  FC                       43.48
  IA                       12.76
  IB                       12.76
  IC                       12.76
C ***** THREE PHASE FAULT BUS C (JOHN DAY)********
  LFA   L2B                     0.0404   {small inductor  in
  LFB   L2C                     0.0404   {           series with
  LFC   L2A                      0.0404    {                   fault
switch
  LFA   L2A                1.E8          {big resistor
  LFB   L2B                1.E8          {        paralell with
  LFC   L2C                  1.E8           {                  fault
switch
  L1A   DA                 1.E8          {big resistor
  L1B   DB                 1.E8          {        paralell with
  L1C   DC                   1.E8           {                  break
switch
  L2A   CA                 1.E8          {big resistor
  L2B   CB                 1.E8          {        paralell with
  L2C   CC                   1.E8           {                  break
switch
BLANK CARD ENDING BRANCH CARDS
C ------------BRAKE SWITCH----------------------------
11B1A                                                            B2A
GATE1A        1
11B2A                                                            B1A
GATE2A        1
11B1B                                                            B2B
GATE1B
11B2B                                                            B1B
GATE2B
11B1C                                                            B2C
GATE1C
11B2C                                                            B1C
GATE2C
C ------------BRAKE SWITCH----------------------------
```

```
C                  11B1A                                                        B2A
brakea
C                  11B1B                                                        B2B
brakeb
C                  11B1C                                                        B2C
brakec
C -------------BRAKE SWITCH------------------------------
C 0B1A   B2A      2.22500   2.72500
C 0B1B   B2B      2.22500   2.72500
C 0B1C   B2C      2.22500   2.72500
C -------------START FAULT SWITCH CARDS------------------
 0L2A   LFA      2.09170   2.20000       1.E22
 0L2B   LFB      2.09170   2.20000       1.E22
 0L2C   LFC      2.09170   2.20000       1.E22
C -------------END OF FAULT SWITCH CARDS-------------------
C -------------START LINE BREAK SWITCH CARDS----------------
C ------- Clear Fault 1.5 cycles after start of fault -------
C ------- Reclose Line 20 cycles after clearing fault -------
11DA    L1A                                                           CLOSED
UA
11DB    L1B                                                           CLOSED
UB
11DC    L1C                                                           CLOSED
UC
11L2A   CA                                                            CLOSED
UA
11L2B   CB                                                            CLOSED
UB
11L2C   CC                                                            CLOSED
UC
C -------------END OF LINE BREAK SWITCH CARDS---------------
BLANK CARD ENDING SWITCH CARDS
C
34567890123456789012345678901234567890123456789012345678901234567890
1234567890
C ------------START GENERATOR CARDS-----------------------------
C ---------Generator 1 (PNW) -------------
59GEN1A     11831.65     60.     77.99                      -1.
  GEN1B
  GEN1C
TOLERANCES                                                 20
PARAMETER FITTING        2.0
 1 1     2       1.       1.    29700.      13.8      800.
BLANK
.0035     .223       .905       .66       .324      .66       .254
.267
7.29       .00      .0300     .04      .093
 1                 1. 31.71865 31718.7
BLANK
  2     1
  3     1
BLANK
C 71EFDGN1
C 72PWRGN1
```

```
C 74W1          2
  FINISH
C ---------Generator 2 (Chief Joe) -------------
59GEN2A     12169.06     60.     81.411                           -1.
  GEN2B
  GEN2C
TOLERANCES                                                     20
PARAMETER FITTING        2.0
 1 1     2         1.         1.      1000.      13.8      800.
BLANK
.0035     .223       .905       .66        .324       .66        .254
.267
7.29      .00        .0300      .04        .093
 1                   1. 5.37     5370.0
BLANK
  2     1
  3     1
BLANK
C 71EFDGN2
C 72PWRGN2
C 74W2          2
  FINISH
C ---------Generator 3 (NC) -------------
59GEN3A     21024.82     60.     12.44                            -1.
  GEN3B
  GEN3C
TOLERANCES                                                     20
PARAMETER FITTING        2.0
 1 1     2         1.         1.   ·  5360.        25.    2000.
BLANK
.0021     .228       1.693      1.636      .346       .991       .281
.281
6.58      1.50       .0430      .1240      .178
 1                   1.  6.0936  6093.6
BLANK
  2     1
  3     1
BLANK
C 71EFDGN3
C 72PWRGN3
C 74W3          2
  FINISH
C
34567890123456789012345678901234567890123456789012345678901234567890
1234567890
C ---------Generator 4 (SC) -------------
59GEN4A     11831.65     60.     3.39                             -1.
  GEN4B
  GEN4C
TOLERANCES                                                     20
PARAMETER FITTING        2.0
 1 1     2         1.         1.    22000.      13.8      800.
BLANK
```

```
.0035     .223      .905      .66       .324      .66       .254
.267
7.29      .00       .0300     .04       .093
 1                1. 21.80657 21806.6
BLANK
  2     1
  3     1
BLANK
C 71EFDGN4
C 72PWRGN4
C 74W4            2
  FINISH
C
34567890123456789012345678901234567890123456789012345678901234567890
1234567890
C ---------Generator 5 (Montana) --------------
59GEN5A     21228.90     60.     33.35                        -1.
  GEN5B
  GEN5C
TOLERANCES                                                  20
PARAMETER FITTING         2.0
 1 1     2         1.         1.      861.0      26.0      800.0
BLANK
.0013     .1284     1.2360    1.2200    .2290     .7260     .1950
.1742
4.5500    .4800     .0790     .0810     .1352
 1                1. 3.325    3325.0
BLANK
  2     1
  3     1
BLANK
C 71EFDGN5
C 72PWRGN5
C 74W4            2
  FINISH
BLANK card ending source cards
C ----------END OF GENERATOR CARDS--------------
C ==========END OF PLANT CARDS===================
$liston
C 111111222222333333444444555555666666777777888888999999
C   BA
C   CA
BLANK card ending plot cards
BLANK
```

Heavy Spring Model

```
BEGIN NEW DATA CASE
C THIS FILE IS FOR TESTING IN 5-MACHINE POWER SYSTEM
 .000400   1.0000    60.
       1       1       1       1       1      -1               1
       1      20     800      50
C ==========START 4-MACHINE PLANT CARDS===================
C
345678901234567890123456789012345678901234567890123456789012345678901234567890
1234567890
C --------START BRAKING RESISTOR CARDS--------------------
C 91D1A          TACS  RR
C 91D1B          TACS  RR
C 91D1C          TACS  RR
C 91F1A          TACS  RR1
C 91F1B          TACS  RR1
C 91F1C          TACS  RR1
C --------END OF BRAKING RESISTOR CARDS--------------------
  GEN2A D1A                 0.001
  GEN2B D1B                 0.001
  GEN2C D1C                 0.001
  GEN3A F1A                 0.001
  GEN3B F1B                 0.001
  GEN3C F1C                 0.001
C ------Transformer cards--------------------------------
  TRANSFORMER                            TR1
            9999
 1GEN1A                            .0001 13.8
 2BA                               1.1102500.0
  TRANSFORMER                            TR2
            9999
 1GEN1B                            .0001 13.8
 2BB                               1.1102500.0
  TRANSFORMER                            TR3
            9999
 1GEN1C                            .0001 13.8
 2BC                               1.1102500.0
  TRANSFORMER                            TR4
            9999
 1D1A                              .0001 13.8
 2DA                               33.5  500.0
  TRANSFORMER                            TR5
            9999
 1D1B                              .0001 13.8
 2DB                               33.5  500.0
  TRANSFORMER                            TR6
            9999
 1D1C                              .0001 13.8
 2DC                               33.5  500.0
```

```
 TRANSFORMER                                 TR10
           9999
1GEN4A                                 .0001 13.8
2IA                                    1.696 500.0
 TRANSFORMER                                 TR11
           9999
1GEN4B                                 .0001 13.8
2IB                                    1.696 500.0
 TRANSFORMER                                 TR12
           9999
1GEN4C                                 .0001 13.8
2IC                                    1.696 500.0
 TRANSFORMER                                 TR7
           9999
1F1A                                   .0001 25.0
2FA                                    8.333 500.0
 TRANSFORMER                                 TR8
           9999
1F1B                                   .0001 25.0
2FB                                    8.333 500.0
 TRANSFORMER                                 TR9
           9999
1F1C                                   .0001 25.0
2FC                                    8.333 500.0
 TRANSFORMER                                 TR13
           9999
1GEN5A                                 .0001 25.0
2HA                                    9.866 500.0
 TRANSFORMER                                 TR14
           9999
1GEN5B                                 .0001 25.0
2HB                                    9.866 500.0
 TRANSFORMER                                 TR15
           9999
1GEN5C                                 .0001 25.0
2HC                                    9.866 500.0
C -----------------Transmission line Parameters----------------
  BA    CA                             21.395
  BB    CB                             21.395
  BC    CC                             21.395
  DA    CA                             162.00
C  L1A   L2A                             324.0
  DB    CB                             162.00
C  L1B   L2B                             324.0
  DC    CC                             162.00
C  L1C   L2C                             324.0
C -------3rd AC Intertie -------
  CA    FA                             220.45
  CB    FB                             220.45
  CC    FC                             220.45
  FA    IA                              47.00
  FB    IB                              47.00
  FC    IC                              47.00
C  CA    FA                             267.45
```

```
C  CB     FB                        267.45
C  CC     FC                        267.45
C ------1st and 2nd AC Intertie ------
  CA     FA                         59.58
  CB     FB                         59.58
  CC     FC                         59.58
  FA     IA                         47.00
  FB     IB                         47.00
  FC     IC                         47.00
C ------Eastern Intertie------
  HA          CA                                                        259.40
3
  HB          CB                                                        259.40
3
  HC          CC                                                        259.40
3
  HA     CA                        259.40
  HB     CB                        259.40
  HC     CC                        259.40
C -----------Shunt Compensation---------------------------
  DA                                     3.459
  DB                                     3.459
  DC                                     3.459
  BA                                     51.15
  BB                                     51.15
  BC                                     51.15
  HA                                     10.63
  HB                                     10.63
  HC                                     10.63
  FA                                     43.00
  FB                                     43.00
  FC                                     43.00
  IA                                     28.31
  IB                                     28.31
  IC                                     28.31
  CA                                     30.48
  CB                                     30.48
  CC                                     30.48
C  -----------Loads-------------------------------------------------
-
  HA                      169.04
  HB                      169.04
  HC                      169.04
  BA                      6.88
  BB                      6.88
  BC                      6.88
  CA                      107.13
  CB                      107.13
  CC                      107.13
  FA                      16.403
  FB                      16.403
  FC                      16.403
  IA                      9.70
  IB                      9.70
```

```
  IC                    9.70
  L1AS  L1B                  0.0404   {small inductor  in
  L1BS  L1C                  0.0404   {              serie with
  L1CS  L1A                   0.0404    {                    fault
switch
  L1AS  L1A             1.E8          {big resistor
  L1BS  L1B             1.E8          {         paralell with
  L1CS  L1C               1.E8           {                   fault
switch
  L1A   DA              1.E8          {big resistor
  L1B   DB              1.E8          {         paralell with
  L1C   DC                1.E8           {                   break
switch
  L2A   CA              1.E8          {big resistor
  L2B   CB              1.E8          {         paralell with
  L2C   CC                1.E8           {                   break
switch
BLANK
C -------------START FAULT SWITCH CARDS------------------
C 0L1A   L1AS   1.1     1.2        1.E22
C 0L1B   L1BS   1.1     1.2        1.E22
C 0L1C   L1CS   1.1     1.2        1.E22
C -------------END OF FAULT SWITCH CARDS-------------------
C -------------START LINE BREAK SWITCH CARDS----------------
C 11DA    L1A                                              CLOSED
UA      1
C 11DB    L1B                                              CLOSED
UB      1
C 11DC    L1C                                              CLOSED
UC      1
C 11L2A   CA                                               CLOSED
UA      1
C 11L2B   CB                                               CLOSED
UB      1
C 11L2C   CC                                               CLOSED
UC      1
C -------------END OF LINE BREAK SWITCH CARDS---------------
C  BA              .001      .05
BLANK
C
34567890123456789012345678901234567890123456789012345678901234567890
1234567890
C ------------START GENERATOR CARDS---------------------------
59GEN1A     11831.65     60.     88.08                          -1.
  GEN1B
  GEN1C
TOLERANCES                                                 20
PARAMETER FITTING        2.0
 1 1     2         1.         1.     48375.      13.8      800.
BLANK
.0035     .223       .905        .66         .324        .66         .254
.267
7.29      .00        .0300      .04        .093
 1                1. 31.71865
```

```
BLANK
C 1         13
  5    2
BLANK
C 71EFDGN1
C 72PWRGN1
C 74W1             2
  FINISH
C
345678901234567890123456789012345678901234567890123456789012345678901234567890
1234567890
59GEN4A      11831.65      60.      24.18                            -1.
  GEN4B
  GEN4C
TOLERANCES                                                         20
PARAMETER FITTING          2.0
 1 1      2          1.          1.     28034.       13.8       800.
BLANK
.0035     .223       .905        .66         .324        .66         .254
.267
7.29       .00       .0300      .04        .093
 1                   1. 21.80657
BLANK
C 1         13
  5    2
BLANK
C 71EFDGN4
C 72PWRGN4
C 74W4             2
  FINISH
59GEN2A      12169.06      60.      92.72                            -1.
  GEN2B
  GEN2C
TOLERANCES                                                         20
PARAMETER FITTING          2.0
 1 1      2          1.          1.     1073.        13.8       800.
BLANK
.0035     .223       .905        .66         .324        .66         .254
.267
7.29       .00       .0300      .04        .093
 1                   1. 5.37
BLANK
C 1         13
  5    2
BLANK
C 71EFDGN2
C 72PWRGN2
C 74W2             2
  FINISH
59GEN3A      21024.82      60.      37.72                            -1.
  GEN3B
  GEN3C
TOLERANCES                                                         20
PARAMETER FITTING          2.0
```

```
 1 1     2          1.          1.     14082.       25.     2000.
BLANK
.0021     .228        1.693      1.636       .346        .991        .281
.281
6.58      1.50       .0430      .1240      .178
 1                  1.  6.0936
BLANK
C 1          13
  5    2
BLANK
C 71EFDGN3
C 72PWRGN3
C 74W3              2
  FINISH
C
345678901234567890123456789012345678901234567890123456789012345678901234567890
1234567890
59GEN5A      21228.90     60.      64.4                              -1.
  GEN5B
  GEN5C
TOLERANCES                                                        20
PARAMETER FITTING         2.0
 1 1     2          1.          1.     2195.0       26.0       800.0
BLANK
.0013     .1284      1.2360     1.2200     .2290       .7260       .1950
.1742
4.5500    .4800      .0790      .0810      .1352
 1                  1. 2.611
BLANK
C 1          13
  5    2
BLANK
C 71EFDGN5
C 72PWRGN5
C 74W4              2
  FINISH
BLANK card ending source cards
C ----------END OF GENERATOR CARDS-------------
C ==========END OF PLANT CARDS==================
C 1
BLANK card ending plot cards
```

Controller 1

```
C ------- BREAKER CONTROL MODEL ----------------
MODELS
INPUT VGEN2A {v(GEN2A)}, VGEN2B {v(GEN2B)}, VGEN2C {v(GEN2C)}
INPUT VD1A {v(D1A)}, VD1B {v(D1B)}, VD1C {v(D1C)}
INPUT VGEN1A {v(GEN1A)}, VGEN1B {v(GEN1B)}, VGEN1C {v(GEN1C)}
INPUT VBB1A {v(BB1A)}, VBB1B {v(BB1B)}, VBB1C {v(BB1C)}
OUTPUT GATE1A,GATE2A,GATE1B,GATE2B,GATE1C,GATE2C
```

```
OUTPUT ua,ub,uc
OUTPUT brakea,brakeb,brakec
MODEL TC1
INPUT v1a,v1b,v1c,v2a,v2b,v2c
  INPUT v3a,v3b,v3c,v4a,v4b,v4c
  VAR pp1,pp2,p,p2,region,t0,pmax,tfault
  VAR e,w,w2,last_w,last_w2,last_p,delta_p,pin,pin2
  VAR g1a,g1b,g1c,g2a,g2b,g2c,vref,last_p2
  VAR brka,brkb,brkc,base_gen,base_gen2
  VAR ILINEA,ILINEB,ILINEC
  VAR ILIN2A,ILIN2B,ILIN2C
  VAR vcontrol1,vcont1,first,brakes
  OUTPUT brka,brkb,brkc
  CONST w0    {VAL:376.991118}
        wmax  {VAL:0.5}
        wmin  {VAL:-0.4}
        h     {VAL:17.9}
        h2    {VAL:3.17}
 INIT
       region:=0.
       pmax:=3500.
       vref:=7.
       tfault:=0.
       w:=0.
       w2:=0.
       p:=1.0
       p2:=1.0
       first:=1.
       vcontrol1:=0.
       brka:=-1.
       brkb:=-1.
       brkc:=-1.
       base_gen:=921900000.0
       base_gen2:=29448000000.0
       brakes:=2.
ENDINIT
 EXEC
C -----START CONTROL SIGNAL CALCULATION-----------------
     last_p:=p
     last_p2:=p2
     last_w:=w
     last_w2:=w2
     e:=t-prevtime
     ILINEA:=1000*(V1A-V2A)
     ILINEB:=1000*(V1B-V2B)
     ILINEC:=1000*(V1C-V2C)
     ILIN2A:=100000000*(V3A-V4A)
     ILIN2B:=100000000*(V3B-V4B)
     ILIN2C:=100000000*(V3C-V4C)
     pp1:=v1a*ilinea+v1b*ilineb+v1c*ilinec
     pp2:=v3a*ilin2a+v3b*ilin2b+v3c*ilin2c
     IF first=1.
       THEN
        base gen:=pp1
```

```
        base_gen2:=pp2
      ENDIF
      pin:=pp1/base_gen
      pin2:=pp2/base_gen2
      p:=pin
      p2:=pin2
      w:= last_w+((2-pin-last_p)*w0/(4*h))*e
      w2:= last_w2+((2-pin2-last_p2)*w0/(4*h2))*e
      IF w2>wmax and region=0. and first=0. and brakes<=2.
        THEN
        brka:=1.
        brkb:=1.
        brkc:=1.
        region:=1.
        brakes:=brakes+1.
      ENDIF
      IF (w2<wmax or (w2>wmax and brakes>2.)) and region=0. and
first=0.
        THEN
        brka:=-1.
        brkb:=-1.
        brkc:=-1.
      ENDIF
      IF region=1. and w<=wmin
        THEN
        brka:=-1.
        brkb:=-1.
        brkc:=-1.
        region:=0.
      ENDIF
      first:=0.
C ----END OF THYRISTOR CONTROLLED VARIABLE CAPACITOR MODEL------
 ENDEXEC
ENDMODEL
USE tc1 AS tc1
  INPUT  v1a:=vgen2a
         v1b:=vgen2b
         v1c:=vgen2c
         v2a:=vd1a
         v2b:=vd1b
         v2c:=vd1c
         v3a:=vgen1a
         v3b:=vgen1b
         v3c:=vgen1c
         v4a:=vbb1a
         v4b:=vbb1b
         v4c:=vbb1c
 OUTPUT  brakea:=brka
         brakeb:=brkb
         brakec:=brkc
ENDUSE
MODEL TC2
  VAR ua1,ub1,uc1,at
  OUTPUT ua1,ub1,uc1
```

```
  INIT ua1:=1.
       ub1:=1.
       uc1:=1.
  ENDINIT
 EXEC
     IF t>=2.1167 AND t<2.4500
       THEN
         ua1:=-1.0
         ub1:=-1.0
         uc1:=-1.0
       ELSE
         ua1:=1.
         ub1:=1.
         uc1:=1.
    ENDIF
 ENDEXEC
ENDMODEL
USE tc2 AS tc2
  OUTPUT ua:=ua1
         ub:=ub1
         uc:=uc1
ENDUSE
RECORD   tc1.p      AS p
         tc1.p2     AS p2
         tc1.region AS region
         tc1.w      AS w
         tc1.w2     AS w2
ENDMODELS
```

Controller 2

```
C ------- BREAKER CONTROL MODEL ----------------
MODELS
INPUT VGEN2A {v(GEN2A)}, VGEN2B {v(GEN2B)}, VGEN2C {v(GEN2C)}
INPUT VD1A {v(D1A)}, VD1B {v(D1B)}, VD1C {v(D1C)}
INPUT VGEN1A {v(GEN1A)}, VGEN1B {v(GEN1B)}, VGEN1C {v(GEN1C)}
INPUT VBB1A {v(BB1A)}, VBB1B {v(BB1B)}, VBB1C {v(BB1C)}
OUTPUT GATE1A,GATE2A,GATE1B,GATE2B,GATE1C,GATE2C
OUTPUT ua,ub,uc
OUTPUT brakea,brakeb,brakec
MODEL TC1
INPUT v1a,v1b,v1c,v2a,v2b,v2c
  INPUT v3a,v3b,v3c,v4a,v4b,v4c
  VAR pp1,pp2,p,p2,region,t0,pmax,tfault
  VAR e,w,w2,last_w,last_w2,last_p,delta_p,pin,pin2
  VAR g1a,g1b,g1c,g2a,g2b,g2c,vref,last_p2
  VAR brka,brkb,brkc,base_gen,base_gen2
  VAR ILINEA,ILINEB,ILINEC
  VAR ILIN2A,ILIN2B,ILIN2C
  VAR vcontrol1,vcont1,first,brakes
  OUTPUT brka,brkb,brkc
```

```
 CONST w0    {VAL:376.991118}
       wmax {VAL:0.5}
       wmin {VAL:-0.4}
       wmin2 {VAL:0.0}
       h    {VAL:17.9}
       h2   {VAL:3.17}
 INIT
      region:=0.
      pmax:=3500.
      vref:=7.
      tfault:=0.
      w:=0.
      w2:=0.
      p:=1.0
      p2:=1.0
      first:=1.
      vcontrol1:=0.
      brka:=-1.
      brkb:=-1.
      brkc:=-1.
      base_gen:=921900000.0
      base_gen2:=29448000000.0
      brakes:=2.
ENDINIT
 EXEC
C -----START CONTROL SIGNAL CALCULATION-----------------
     last_p:=p
     last_p2:=p2
     last_w:=w
     last_w2:=w2
     e:=t-prevtime
     ILINEA:=1000*(V1A-V2A)
     ILINEB:=1000*(V1B-V2B)
     ILINEC:=1000*(V1C-V2C)
     ILIN2A:=100000000*(V3A-V4A)
     ILIN2B:=100000000*(V3B-V4B)
     ILIN2C:=100000000*(V3C-V4C)
     pp1:=v1a*ilinea+v1b*ilineb+v1c*ilinec
     pp2:=v3a*ilin2a+v3b*ilin2b+v3c*ilin2c
     IF first=1.
       THEN
        base_gen:=pp1
        base_gen2:=pp2
     ENDIF
     pin:=pp1/base_gen
     pin2:=pp2/base_gen2
     p:=pin
     p2:=pin2
     w:= last_w+((2-pin-last_p)*w0/(4*h))*e
     w2:= last_w2+((2-pin2-last_p2)*w0/(4*h2))*e
     IF w2>wmax and region=0. and first=0. and brakes<=2.
       THEN
        brka:=1.
        brkb:=1.
```

```
        brkc:=1.
        region:=1.
        brakes:=brakes+1.
      ENDIF
      IF  (w2<wmax  or  (w2>wmax  and  brakes>2.))  and  region=0.  and
first=0.
        THEN
        brka:=-1.
        brkb:=-1.
        brkc:=-1.
      ENDIF
      IF region=1. and w<=wmin
        THEN
        brka:=-1.
        brkb:=-1.
        brkc:=-1.
        region:=2.
        ENDIF
      IF region=2. and w>=wmax
        THEN
        brka:=1.
        brkb:=1.
        brkc:=1.
        region:=3.
      ENDIF
      IF region=3. and w<=wmin2
        THEN
        brka:=-1.
        brkb:=-1.
        brkc:=-1.
        region:=0.
        ENDIF
      first:=0.
C ----END OF THYRISTOR CONTROLLED VARIABLE CAPACITOR MODEL------
 ENDEXEC
ENDMODEL
USE tc1 AS tc1
  INPUT  v1a:=vgen2a
         v1b:=vgen2b
         v1c:=vgen2c
         v2a:=vd1a
         v2b:=vd1b
         v2c:=vd1c
         v3a:=vgen1a
         v3b:=vgen1b
         v3c:=vgen1c
         v4a:=vbb1a
         v4b:=vbb1b
         v4c:=vbb1c
 OUTPUT  brakea:=brka
         brakeb:=brkb
         brakec:=brkc
ENDUSE
MODEL TC2
```

```
   VAR ua1,ub1,uc1,at
   OUTPUT ua1,ub1,uc1
   INIT ua1:=1.
        ub1:=1.
        uc1:=1.
   ENDINIT
  EXEC
      IF t>=2.1167 AND t<2.4500
        THEN
          ua1:=-1.0
          ub1:=-1.0
          uc1:=-1.0
        ELSE
          ua1:=1.
          ub1:=1.
          uc1:=1.
     ENDIF
  ENDEXEC
ENDMODEL
USE tc2 AS tc2
  OUTPUT ua:=ua1
         ub:=ub1
         uc:=uc1
ENDUSE
RECORD   tc1.p      AS p
         tc1.p2     AS p2
         tc1.region AS region
         tc1.w      AS w
         tc1.w2     AS w2
ENDMODELS
```

Breaker Switched Controller 3

```
C ------- BREAKER CONTROL MODEL -----------------
MODELS
INPUT VGEN2A {v(GEN2A)}, VGEN2B {v(GEN2B)}, VGEN2C {v(GEN2C)}
INPUT VD1A {v(D1A)}, VD1B {v(D1B)}, VD1C {v(D1C)}
INPUT VGEN1A {v(GEN1A)}, VGEN1B {v(GEN1B)}, VGEN1C {v(GEN1C)}
INPUT VBB1A {v(BB1A)}, VBB1B {v(BB1B)}, VBB1C {v(BB1C)}
OUTPUT GATE1A,GATE2A,GATE1B,GATE2B,GATE1C,GATE2C
OUTPUT ua,ub,uc
OUTPUT brakea,brakeb,brakec
MODEL TC1
INPUT v1a,v1b,v1c,v2a,v2b,v2c
  INPUT v3a,v3b,v3c,v4a,v4b,v4c
  VAR pp1,pp2,p,p2,region,t0,pmax,tfault
  VAR e,w,w2,last_w,last_w2,last_p,delta_p,pin,pin2
  VAR g1a,g1b,g1c,g2a,g2b,g2c,vref,last_p2
  VAR brka,brkb,brkc,base_gen,base_gen2
  VAR ILINEA,ILINEB,ILINEC
  VAR ILIN2A,ILIN2B,ILIN2C
```

```
  VAR vcontrol1,vcont1,first,brakes
  VAR pbrake
  OUTPUT brka,brkb,brkc
  CONST w0    {VAL:376.991118}
        wmax {VAL:0.5}
        wmin {VAL:-0.45}
        wmin2 {VAL:0.0}
        h     {VAL:17.9}
        h2    {VAL:3.17}
        k1    {VAL:2600.0}
        k2    {VAL:2600.0}
        tau   {VAL:3.0}
        tau2 {VAL:1.5}
 INIT
      region:=0.
      pmax:=3500.
      vref:=7.
      tfault:=0.
      w:=0.
      w2:=0.
      p:=1.0
      p2:=1.0
      first:=1.
      vcontrol1:=0.
      brka:=-1.
      brkb:=-1.
      brkc:=-1.
      base_gen:=921900000.0
      base_gen2:=29448000000.0
      brakes:=2.
      pbrake:=0.
ENDINIT
 EXEC
C -----START CONTROL SIGNAL CALCULATION------------------
     last_p:=p
     last_p2:=p2
     last_w:=w
     last_w2:=w2
     e:=t-prevtime
     ILINEA:=1000*(V1A-V2A)
     ILINEB:=1000*(V1B-V2B)
     ILINEC:=1000*(V1C-V2C)
     ILIN2A:=100000000*(V3A-V4A)
     ILIN2B:=100000000*(V3B-V4B)
     ILIN2C:=100000000*(V3C-V4C)
     pp1:=v1a*ilinea+v1b*ilineb+v1c*ilinec
     pp2:=v3a*ilin2a+v3b*ilin2b+v3c*ilin2c
     IF first=1.
       THEN
        base_gen:=pp1
        base_gen2:=pp2
     ENDIF
     pin:=pp1/base_gen
     pin2:=pp2/base_gen2
```

```
      p:=pin
      p2:=pin2
      w:= last_w+((2-pin-last_p)*w0/(4*h))*e
      w2:= last_w2+((2-pin2-last_p2)*w0/(4*h2))*e
      IF w2>wmax and region=0. and first=0. and brakes<=2.
        THEN
         t0:=t
         pmax:=1.0-pin2
         region:=1.
         brakes:=brakes+1.
      ENDIF
      IF  (w2<wmax  or  (w2>wmax  and  brakes>2.))  and  region=0.  and
first=0.
        THEN
         pbrake:=0.
      ENDIF
      IF region=1. and w>wmin
        THEN
         pbrake:=pmax*k1*exp(-tau*(t-t0))
        ENDIF
      IF region=1. and w<=wmin
        THEN
         pbrake:=0.
         region:=2.
        ENDIF
      IF region=2. and w>=wmax
        THEN
         t0:= t
         region:=3.
      ENDIF
      IF region=3. and w>wmin2
        THEN
         pbrake:=pmax*k2*exp(-tau2*(t-t0))
      ENDIF
      IF region=3. and w<=wmin2
        THEN
         pbrake:=0.
         region:=0.
      ENDIF
      first:=0.
C ----Give power Output Command ------------------------------
      IF pbrake > 933.3
        THEN
        brka:=1.
        brkb:=1.
        brkc:=1.
      ENDIF
      IF pbrake < 933.3 and pbrake > 500.0
        THEN
        brka:=1.
        brkb:=1.
        brkc:= -1.
      ENDIF
      IF pbrake < 500.0 and pbrake > 100.0
```

```
        THEN
        brka:=1.
        brkb:= -1.
        brkc:= -1.
      ENDIF
      IF pbrake <=100.0
        THEN
        brka:= -1.
        brkb:= -1.
        brkc:= -1.
      ENDIF
C ----END OF THYRISTOR CONTROLLED VARIABLE BRAKE MODEL------
 ENDEXEC
ENDMODEL
USE tc1 AS tc1
  INPUT  v1a:=vgen2a
         v1b:=vgen2b
         v1c:=vgen2c
         v2a:=vd1a
         v2b:=vd1b
         v2c:=vd1c
         v3a:=vgen1a
         v3b:=vgen1b
         v3c:=vgen1c
         v4a:=vbb1a
         v4b:=vbb1b
         v4c:=vbb1c
 OUTPUT  brakea:=brka
         brakeb:=brkb
         brakec:=brkc
ENDUSE
MODEL TC2
  VAR ua1,ub1,uc1,at
  OUTPUT ua1,ub1,uc1
  INIT ua1:=1.
       ub1:=1.
       uc1:=1.
  ENDINIT
 EXEC
     IF t>=2.1167 AND t<2.4500
       THEN
         ua1:=-1.0
         ub1:=-1.0
         uc1:=-1.0
       ELSE
         ua1:=1.
         ub1:=1.
         uc1:=1.
    ENDIF
 ENDEXEC
ENDMODEL
USE tc2 AS tc2
  OUTPUT ua:=ua1
         ub:=ub1
```

```
        uc:=uc1
ENDUSE
RECORD  tc1.p      AS p
        tc1.p2     AS p2
        tc1.region AS region
        tc1.w      AS w
        tc1.w2     AS w2
        tc1.pbrake AS pbrake
ENDMODELS
```

Thyristor Switched Controller 3

```
C ------- Thyristor CONTROL MODEL ----------------
MODELS
INPUT VGEN2A {v(GEN2A)}, VGEN2B {v(GEN2B)}, VGEN2C {v(GEN2C)}
INPUT VD1A {v(D1A)}, VD1B {v(D1B)}, VD1C {v(D1C)}
INPUT VDA {v(DA)}, VDB {v(DB)}, VDC {v(DC)}
INPUT VB1A {v(B1A)}, VB1B {v(B1B)}, VB1C {v(B1C)}
INPUT VGEN1A {v(GEN1A)}, VGEN1B {v(GEN1B)}, VGEN1C {v(GEN1C)}
INPUT VBB1A {v(BB1A)}, VBB1B {v(BB1B)}, VBB1C {v(BB1C)}
OUTPUT GATE1A,GATE2A,GATE1B,GATE2B,GATE1C,GATE2C
OUTPUT ua,ub,uc
MODEL TC1
  INPUT v1a,v1b,v1c,v2a,v2b,v2c
  INPUT v5a,v5b,v5c,v6a,v6b,v6c
  INPUT v3a,v3b,v3c,v4a,v4b,v4c
  VAR pp1,pp2,region,t0,pmax
  VAR e,w,w2,last_w,last_w2,last_p,pin,pin2
  VAR g1a,g1b,g1c,g2a,g2b,g2c,vref,last_p2
  VAR base_gen,base_gen2
  VAR ILINEA,ILINEB,ILINEC
  VAR ILIN2A,ILIN2B,ILIN2C
  VAR vcontrol1,vcont1,first,brakes
  VAR pbrake,pactual,pact1st,pmeas,pactdlt
  VAR ALPHA,VCONTROL
  VAR RAMPA,COMPA,DCMPA
  VAR RAMPAN,COMPAN,DCMPAN
  VAR RAMPB,COMPB,DCMPB
  VAR RAMPBN,COMPBN,DCMPBN
  VAR RAMPC,COMPC,DCMPC
  VAR RAMPCN,COMPCN,DCMPCN
  OUTPUT g1a,g2a,g1b,g2b,g1c,g2c
  CONST w0    {VAL:376.991118}
        wmax {VAL:0.2}
        wmax2 {VAL:0.5}
        wmin {VAL:-0.6}
        wmin2 {VAL:-0.2}
        h     {VAL:17.9}
        h2    {VAL:3.17}
        k1    {VAL:1800.0}
        k2    {VAL:1200.0}
```

```
        tau   {VAL:5.0}
        tau2  {VAL:1.5}
 INIT
      region:=0.
      vref:=7.
      w:=0.
      w2:=0.
      pin:=1.0
      pin2:=1.0
      pmax:=0.0
      first:=1.
      vcontrol1:=0.
      base_gen:=921900000.0
      base_gen2:=29448000000.0
      brakes:=2.
      pbrake:=0.
      pactual:=0.
      rampa:=0.
      rampan:=0.
      rampb:=0.
      rampbn:=0.
      rampc:=0.
      rampcn:=0.
      compa:=0.
      compan:=0.
      compb:=0.
      compbn:=0.
      compc:=0.
      compcn:=0.
ENDINIT
 EXEC
C -----START CONTROL SIGNAL CALCULATION-----------------
     last_p:=pin
     last_p2:=pin2
     last_w:=w
     last_w2:=w2
     pactlst:=pactual
     e:=t-prevtime
     ILINEA:=1000*(V1A-V2A)
     ILINEB:=1000*(V1B-V2B)
     ILINEC:=1000*(V1C-V2C)
     ILIN2A:=100000000*(V3A-V4A)
     ILIN2B:=100000000*(V3B-V4B)
     ILIN2C:=100000000*(V3C-V4C)
     pp1:=v1a*ilinea+v1b*ilineb+v1c*ilinec
     pp2:=v3a*ilin2a+v3b*ilin2b+v3c*ilin2c
     IF first=1.
       THEN
        base_gen:=pp1
        base_gen2:=pp2
     ENDIF
     pin:=pp1/base_gen
     pin2:=pp2/base_gen2
     IF (1-pin2) >pmax
```

```
      THEN
        pmax:=(1-pin2)
    ENDIF
    w:= last_w+((2-pin-last_p)*w0/(4*h))*e
    w2:= last_w2+((2-pin2-last_p2)*w0/(4*h2))*e
    IF w2>wmax and region=0. and first=0. and brakes<=2.
      THEN
        t0:=t
        region:=1.
        brakes:=brakes+1.
    ENDIF
    IF region=1. and w>wmin
      THEN
        pbrake:=pmax*k1*exp(-tau*(t-t0))
      ENDIF
    IF region=1. and (w<=wmin or (w>=wmax2 and last_w<wmax2))
      THEN
        pbrake:=0.
        region:=2.
      ENDIF
    IF region=2. and w>=wmax2
      THEN
        t0:= t
        region:=3.
    ENDIF
    IF region=3. and w>wmin2
      THEN
        pbrake:=pmax*k2*exp(-tau2*(t-t0))
    ENDIF
    IF region=3. and w<=wmin2
      THEN
        pbrake:=0.
        region:=0.
    ENDIF
    pmeas:=0.001*((V5A*(V5A-V6A))+(V5B*(V5B-V6B))+(V5C*(V5C-V6C)))
    pactdlt:=(-60.0*pactlst + 60.0*pmeas)*e
    pactual:=1.0*(pactlst+pactdlt)
    pbrake:=pbrake + 4*(pbrake - pactual)
    IF pbrake > 1400.
      THEN
        pbrake:=1400.
    ENDIF
    IF pbrake <= 0.0
      THEN
        pbrake:=0.0
    ENDIF
    ALPHA:=(180/1.5708)*acos(pbrake/1405.)
    IF ALPHA > 160.
      THEN
        ALPHA:=200.
    ENDIF
    VCONTL:=1000.0*ALPHA/180.0
    first:=0.
C --------END OF CONTROL SIGNAL CALCULATION---------------
```

```
C -------START THYRISTOR CONTROLLED VARIABLE BRAKE MODEL---
      IF v5a>=0.
        THEN
          vcontrol1:=vcont1
          rampa:=rampa+timestep*1.2e+5
      ELSE
          rampa:=0.
      ENDIF
         dcmpa:=compa
         compa:=bool(rampa-vcont1)
         g1a:=and(nor(dcmpa),compa)
      IF v5a<0.
         THEN
          rampan:=rampan+timestep*1.2e+5
      ELSE
          rampan:=0.0
      ENDIF
         dcmpan:=compan
         compan:=bool(rampan-vcontrol1)
         g2a:=and(nor(dcmpan),compan)
      IF v5b>=0.
         THEN
          vcontrol1:=vcont1
          rampb:=rampb+timestep*1.2e+5
      ELSE
          rampb:=0.
      ENDIF
         dcmpb:=compb
         compb:=bool(rampb-vcont1)
         g1b:=and(nor(dcmpb),compb)
      IF v5b<0.
         THEN
          rampbn:=rampbn+timestep*1.2e+5
      ELSE
          rampbn:=0.
      ENDIF
         dcmpbn:=compbn
         compbn:=bool(rampbn-vcontrol1)
         g2b:=and(nor(dcmpbn),compbn)
      IF v5c>=0.
         THEN
          vcontrol1:=vcont1
          rampc:=rampc+timestep*1.2e+5
      ELSE
          rampc:=0.
      ENDIF
         dcmpc:=compc
         compc:=bool(rampc-vcont1)
         g1c:=and(nor(dcmpc),compc)
      IF v5c<0.
         THEN
          rampcn:=rampcn+timestep*1.2e+5
      ELSE
          rampcn:=0.
```

```
      ENDIF
         dcmpcn:=compcn
         compcn:=bool(rampcn-vcontrol1)
         g2c:=and(nor(dcmpcn),compcn)
C ----END OF THYRISTOR CONTROLLED VARIABLE brake MODEL------
 ENDEXEC
ENDMODEL
USE tc1 AS tc1
  INPUT  v1a:=vgen2a
         v1b:=vgen2b
         v1c:=vgen2c
         v2a:=vd1a
         v2b:=vd1b
         v2c:=vd1c
         v3a:=vgen1a
         v3b:=vgen1b
         v3c:=vgen1c
         v4a:=vbb1a
         v4b:=vbb1b
         v4c:=vbb1c
         v5a:=vda
         v5b:=vdb
         v5c:=vdc
         v6a:=vb1a
         v6b:=vb1b
         v6c:=vb1c
OUTPUT  gate1a:=g1a
         gate2a:=g2a
         gate1b:=g1b
         gate2b:=g2b
         gate1c:=g1c
         gate2c:=g2c
ENDUSE
MODEL TC2
  VAR ua1,ub1,uc1,at
  OUTPUT ua1,ub1,uc1
  INIT ua1:=1.
       ub1:=1.
       uc1:=1.
  ENDINIT
 EXEC
     IF t>=2.1167 AND t<2.4500
       THEN
         ua1:=-1.0
         ub1:=-1.0
         uc1:=-1.0
       ELSE
         ua1:=1.
         ub1:=1.
         uc1:=1.
    ENDIF
 ENDEXEC
ENDMODEL
USE tc2 AS tc2
```

```
  OUTPUT ua:=ua1
         ub:=ub1
         uc:=uc1
ENDUSE
RECORD   tc1.pin     AS pin
         tc1.pin2    AS pin2
         tc1.pmeas   AS pmeas
         tc1.w       AS w
         tc1.w2      AS w2
         tc1.pbrake  AS pbrake
         tc1.pactual AS pact
ENDMODELS
```

Appendix B SMIB Model Controller Software

```
;This Program is for operation of the SMIB Thyristor ;switched
brake.
;
.286C
;MODULE EQUATES
        BASE_ADDR EQU 360H
        ADC0      EQU BASE_ADDR + 00H
        ADCHI     EQU BASE_ADDR + 02H
        DAC0      EQU BASE_ADDR + 04H
        DAC1      EQU BASE_ADDR + 06H
        PA        EQU BASE_ADDR + 0CH
        PB        EQU BASE_ADDR + 0DH
        PC        EQU BASE_ADDR + 0EH
        PCON      EQU BASE_ADDR + 0FH

SSEG     SEGMENT STACK
        DW  128 DUP(0)
SSEG     ENDS

DSEG     SEGMENT
        Vref1     dw 20839,20891,20942,20991,21040,21087,21132
                    dw 21177,21221,21263,21304,21345,21384,21422
                    dw 21460,21496,21532,21567,21600,21633,21665
        Vref2     dw 18702,18809,18914,19015,19114,19211,19305
                    dw 19396,19485,19572,19656,19738,19818,19896
                    dw 19972,20046,20119,20189,20257,20324,20389
        Vref3     dw 16466,16636,16802,16962,17118,17270,17417
                    dw 17559,17698,17833,17964,18091,18215,18336
                    dw 18453,18567,18678,18786,18891,18993,19093
        Vref4     dw 14052,14302,14542,14775,14999,15216,15425
                    dw 15628,15824,16015,16199,16377,16551,16719
                    dw 16882,17040,17193,17343,17487,17628,17765
        Vref5     dw 11317,11680,12026,12357,12673,12975,13266
                    dw 13545,13813,14071,14320,14560,14792,15015
                    dw 15231,15441,15643,15839,16028,16212,16390
        Vref6     dw 7899,8480,9015,9510,9974,10409,10819
                    dw 11207,11576,11927,12262,12582,12888,13182
                    dw 13464,13735,13996,14248,14491,14725,14951
        Vref7     dw 0,3251,4578,5584,6421,7148,7798
                      dw 8387,8929,9430,9899,10338,10752,11144
                    dw 11516,11870,12207,12529,12838,13134,13418
        Vref_current dw 0
        MEAS_N1 DW 0
        MEAS_N2 DW 0
        MEAS_N3 DW 0
        MEAS_N4 DW 0
        MEAS_N5 DW 0
        MEAS_N6 DW 0
```

```
        MEAS_N7 DW 0
        MEAS_N8 DW 0
        MEAS_N9 DW 0
        MEAS_N10 DW 0
        MEAS_N11 DW 0
        MEAS_N12 DW 0
        MEAS_N13 DW 0
        MEAS_N14 DW 0
        MEAS_N15 DW 0
        MEAS_N16 DW 0
        MEAS_N17 DW 0
        MEAS_N18 DW 0
        MEAS_N19 DW 0
        MEAS_N20 DW 0
        brakes dw 0
        t dw 0
        brakes_max dw 2
        last_pwr  dw 0
        last_w     dw 0
        p0         dw 0
        last_meas dw 0
        wmin  equ 00dfh
        w0    equ 0000h
;         wmin  equ 00cfh
;         w0    equ 0010h
DSEG      ENDS

CSEG      SEGMENT PUBLIC
        ASSUME  CS:CSEG,DS:DSEG,SS:SSEG
BEGIN:    MOV AX,DSEG          ;data segment in DS
        MOV DS,AX

set_con: MOV DX, PCON
        MOV AL, 10010010B
        OUT DX, AX
;RESET
        MOV DX, PC
        MOV AL, 11111110b
        OUT DX, AL

initial: call brake_off
        CALL AIN
        MOV MEAS_N20, AX
        CALL AIN
        MOV MEAS_N19, AX
        CALL AIN
        MOV MEAS_N18, AX
        CALL AIN
        MOV MEAS_N17, AX
        CALL AIN
        MOV MEAS_N16, AX
        CALL AIN
        MOV MEAS_N15, AX
        CALL AIN
```

```
        MOV MEAS_N14, AX
        CALL AIN
        MOV MEAS_N13, AX
        CALL AIN
        MOV MEAS_N12, AX
        CALL AIN
        MOV MEAS_N11, AX
        CALL AIN
        MOV MEAS_N10, AX
        CALL AIN
        MOV MEAS_N9, AX
        CALL AIN
        MOV MEAS_N8, AX
        CALL AIN
        MOV MEAS_N7, AX
        CALL AIN
        MOV MEAS_N6, AX
        CALL AIN
        MOV MEAS_N5, AX
        CALL AIN
        MOV MEAS_N4, AX
        CALL AIN
        MOV MEAS_N3, AX
        CALL AIN
        MOV MEAS_N2, AX
        CALL AIN
        MOV MEAS_N1, AX
        call ain2
        mov last_meas, ax
        call power
        mov last_pwr,ax
        mov p0, ax
get_pwr: call power

; check for program exit
        PUSH AX
        CALL GET_KB_CHAR
        CMP AX, 27
        JNE cont
        MOV  AH,4CH             ;return to DOS
        INT  21H
cont:    pop ax

omega:   mov bx,last_pwr
        mov last_pwr, ax
        sub ax,bx
        mov bx, p0
        shl bx,1
        sub bx,ax
        mov ax, last_w
        add ax,bx
        mov last_w, ax
        mov bx, wmin
        cmp ax,bx
```

```
        jl get_pwr

apply_brake:
        mov ax, brakes
        inc ax
        mov brakes, ax
Det_w:
Look_up: mov SI, t
        mov bx, offset Vref6
        MOV AX, [BX + SI]
Output_volt:
        add ax, 0A777h
        call aout
Inc_time:
        mov cx, t
        ADD Cx, 2
        mov t, cx

        call power
        mov bx,last_pwr
        mov last_pwr, ax
        sub ax,bx
        mov bx, p0
        shl bx,1
        sub bx,ax
        mov ax, last_w
        add ax,bx
        mov last_w, ax
        mov bx, w0
        cmp ax, bx
        jg Det_w


Switch_off:
        call brake_off
        mov ax,t
        xor ax,ax
        mov t,ax
        mov ax, brakes
        mov bx, brakes_max
        cmp ax, bx
        jl omega

brake_on proc

     mov ax,08fffh
     call aout
     ret

brake_on endp

brake_off proc

     mov ax,0ffffh
```

```
      call aout
      ret

brake_off endp

power proc
      push bx
      push cx
      push dx
      call ain2
      mov bx, ax
      call ain2
      add ax, bx
      shr ax,1
      pop dx
      pop cx
      pop dx
      ret
power endp


endprogram:
        MOV   AH,4CH           ;return to DOS
        INT   21H

include ain.asm
include aout.asm
include filter3.asm
include filter5.asm
include ain2.asm
include getkbchr.asm
include pause.asm
include resort.asm
cseg ends

end begin
```

Appendix C BPA Transient Stability Studies

Fault	GEN* / KV* / EMWS*	ASHE 2 / 25.0 1 / 4443	BOARD F / 24.0 1 / 1518	BONN PH2 / 13.8 1 / 1456	CENTR G1 / 20.0 1 / 2204	CENTR G2 / 20.0 1 / 2204	CHIEF J5 / 13.8 1 / 3263.7
1	GRIZZLY	732.43	457.58	169.80	271.03	271.73	215.03
7	ALVEY	519.74	269.04	146.38	244.49	245.13	163.20
8	DIXONVLE	428.48	232.78	122.12	196.82	197.23	131.62
10	MERIDINP	381.75	226.39	111.76	167.97	168.20	112.14
11	CPT JAC	599.72	407.94	163.12	228.71	228.90	165.21
13	SUMMER L	472.48	302.12	118.99	177.85	178.13	135.62
15	BURNS	219.50	126.70	51.29	83.75	83.93	66.54
16	MIDPOINT	59.99	13.47	7.59	24.90	25.06	24.13
18	PONDROSA	557.49	359.92	139.07	207.34	207.68	159.43
20	MALIN	607.73	414.52	164.72	230.71	230.90	167.22
23	OLINDA	315.51	237.90	93.77	118.43	118.36	80.99
24	ROUND MT	462.42	337.78	133.01	173.75	173.73	121.48
28	MARION	727.33	346.19	149.32	335.81	337.44	238.19
30	PEARL	683.01	313.16	232.87	447.06	449.60	265.08
34	KEELER	558.96	240.28	183.61	460.71	463.72	246.02
40	SANTIAM	716.25	348.81	167.29	335.23	336.73	233.37
41	ALLSTON	434.69	161.44	109.45	567.18	574.05	260.94
42	PAUL	345.76	113.13	76.18	644.04	642.68	272.32
43	RAVER	368.73	81.83	44.77	303.36	308.85	472.94
44	SATSOP	189.09	61.39	43.64	355.80	359.97	155.77
45	OLYMPIA	251.34	82.69	59.06	461.78	468.55	206.45
46	TACOMA	236.22	47.27	22.39	185.60	188.68	305.71
47	COVINGTN	258.22	52.52	26.17	205.20	208.56	334.68
48	MAPLE VL	244.29	46.82	21.38	181.89	185.10	343.52
49	ECHOLAKE	286.46	57.68	28.46	220.45	224.35	398.81
50	MONROE	171.64	21.41	6.64	114.55	117.00	313.93
51	OSTRANDR	654.61	294.15	222.88	383.61	385.58	247.10
52	TROUTDAL	466.69	210.06	193.14	276.30	277.58	177.81
53	MCLOUGLN	558.21	249.09	184.64	328.22	329.86	212.03
54	SCHULTZ	384.87	68.13	33.85	227.56	232.11	515.87
55	VANTAGE	532.96	98.49	50.96	209.08	211.13	348.67
56	HANFORD	927.57	209.71	107.75	318.01	320.98	389.18
57	ASHE	1086.77	188.25	96.72	246.86	248.61	310.28
58	LOW MON	635.85	110.46	60.76	176.13	177.44	227.42
59	LIT GOOS	441.06	63.10	38.39	127.19	128.19	169.32
60	LOW GRAN	283.50	22.91	20.06	87.96	88.74	122.44
61	HATWAI	111.49	-21.90	0.09	45.44	46.02	71.51
62	DWORSHAK	30.64	-38.86	-8.29	23.36	23.82	43.34
63	SACJWA T	519.15	126.72	57.90	146.72	147.60	174.55
64	MCNARY	561.92	213.93	82.68	172.88	173.73	180.14
65	TABLE MT	399.78	302.05	118.42	149.45	149.37	102.47
66	VACA-DIX	322.01	253.56	98.91	119.60	119.47	79.93
67	CUSTERW	77.23	4.86	-0.20	52.63	53.77	144.92
68	ING500	61.13	1.12	-2.25	39.59	40.59	118.01
69	TAFT	-65.15	-55.86	-18.55	-7.47	-7.15	0.84
70	GARRISON	-74.90	-50.43	-17.54	-13.31	-13.09	-11.30
71	HOT SPR	-45.16	-36.37	-12.37	-6.29	-6.09	-1.88
72	BELL	-28.29	-32.43	-12.18	-4.50	-4.22	3.24
77	COULEE	281.47	23.12	9.97	126.93	130.10	513.76

Table D.1 Light Autumn Generation Individual Acceleration Power Based On System Faults

FAULT	GEN* KV* EMWS*	CHIEF JO 13.8 1 1808	COULEE 2 13.8 1 10314	COULEE51 15.0 1 9132	DALLES 3 13.8 1 2072	DIABLO 13.8 1 570.6	HUNGRY H 13.8 1 2096
1	GRIZZLY	114.38	666.42	466.42	391.53	14.92	44.82
7	ALVEY	86.79	496.75	346.77	237.15	11.77	30.83
8	DIXONVLE	70.33	400.63	282.57	204.86	9.66	24.49
10	MERIDINP	60.54	341.81	247.08	200.29	8.57	19.94
11	CPT JAC	89.95	508.67	375.41	354.18	12.79	29.95
13	SUMMER L	72.84	419.64	298.34	260.13	9.84	28.52
15	BURNS	35.26	207.06	140.37	106.55	4.51	17.63
16	MIDPOINT	11.93	76.73	41.50	7.29	1.11	15.00
18	PONDROSA	85.58	492.96	351.41	310.73	11.54	32.42
20	MALIN	91.05	515.07	380.13	359.76	12.93	30.45
23	OLINDA	45.09	249.01	193.45	211.66	6.87	12.13
24	ROUND MT	67.12	373.57	285.16	297.48	9.98	19.66
28	MARION	124.59	729.92	491.69	297.79	15.80	48.14
30	PEARL	138.81	801.37	536.89	312.65	18.39	47.93
34	KEELER	128.13	734.65	482.32	233.18	17.13	43.08
40	SANTIAM	122.53	713.78	484.83	307.68	15.77	46.21
41	ALLSTON	133.18	760.28	472.12	144.62	17.07	41.29
42	PAUL	135.83	781.35	457.50	96.31	15.63	39.23
43	RAVER	219.97	1298.42	710.77	65.03	14.46	61.31
44	SATSOP	78.31	444.13	257.21	50.09	9.34	21.70
45	OLYMPIA	104.04	593.09	345.30	68.84	12.64	28.43
46	TACOMA	139.99	819.25	441.03	32.40	4.25	40.86
47	COVINGTN	152.68	900.89	485.09	37.36	4.33	44.59
48	MAPLE VL	159.70	890.30	468.39	31.80	7.99	44.22
49	ECHOLAKE	185.56	1043.03	553.35	41.85	10.81	50.87
50	MONROE	141.02	726.78	327.05	10.27	2.66	39.99
51	OSTRANDR	129.19	751.66	503.12	309.12	16.73	46.34
52	TROUTDAL	92.97	539.19	358.70	217.30	12.00	33.12
53	MCLOUGLN	110.71	643.53	428.70	259.76	14.25	39.91
54	SCHULTZ	224.99	1483.83	792.89	54.99	5.19	72.97
55	VANTAGE	163.90	1089.80	589.81	82.48	12.89	73.96
56	HANFORD	187.42	1240.78	729.44	237.48	16.52	105.88
57	ASHE	152.30	993.02	590.64	171.64	14.15	98.85
58	LOW MON	111.09	752.31	411.72	97.90	9.63	119.68
59	LIT GOOS	82.26	573.10	293.14	54.10	6.67	122.44
60	LOW GRAN	58.65	427.87	197.59	20.83	4.21	128.50
61	HATWAI	32.40	268.60	92.83	-13.83	1.43	150.57
62	DWORSHAK	17.82	170.25	38.88	-26.94	0.06	157.80
63	SACJWA T	86.98	569.82	326.52	93.92	8.27	78.17
64	MCNARY	91.53	580.16	351.86	145.74	9.65	64.25
65	TABLE MT	57.06	315.02	244.94	268.14	8.69	15.41
66	VACA-DIX	44.98	245.77	195.80	227.35	7.07	10.78
67	CUSTERW	64.34	333.81	130.25	-1.29	-0.57	23.12
68	ING500	51.17	272.42	96.40	-4.05	-1.97	21.04
69	TAFT	-8.03	-26.38	-50.13	-40.61	-2.34	219.83
70	GARRISON	-13.24	-90.08	-62.10	-36.86	-2.41	118.78
71	HOT SPR	-6.66	-32.06	-36.83	-26.70	-1.62	218.66
72	BELL	-8.37	-21.00	-43.82	-25.23	-2.12	152.67
77	COULEE	204.11	1807.83	928.86	17.08	-6.13	80.67

Table D.1 Continued

FAULT	GEN* KV* EMWS*	ICE H3-4 13.8 1 310	JOHN DAY 13.8 1 7856	LIBBY 13.8 1 2680	LIT GOOS 13.8 1 2946	LOW GRAN 13.8 1 2946	LOW MON 13.8 1 2946
1	GRIZZLY	58.68	439.47	28.02	94.08	87.68	96.13
7	ALVEY	38.56	239.94	19.52	64.13	60.09	65.45
8	DIXONVLE	31.92	214.18	15.41	52.98	49.38	54.26
10	MERIDINP	28.87	222.29	12.38	47.53	43.64	49.05
11	CPT JAC	47.53	428.89	18.21	76.56	69.39	79.46
13	SUMMER L	37.42	293.42	17.50	60.63	56.38	62.09
15	BURNS	17.13	106.30	10.76	28.36	27.48	28.44
16	MIDPOINT	4.12	-13.22	9.13	7.60	9.16	6.80
18	PONDROSA	44.33	353.09	20.03	71.41	66.12	73.30
20	MALIN	48.23	436.23	18.50	77.66	70.39	80.59
23	OLINDA	25.16	269.50	7.10	40.31	35.43	42.47
24	ROUND MT	36.81	374.24	11.68	59.08	52.50	61.93
28	MARION	53.88	285.71	30.87	89.87	85.32	90.87
30	PEARL	52.03	269.42	31.11	86.15	82.17	86.91
34	KEELER	42.43	186.59	28.29	70.56	68.44	70.57
40	SANTIAM	53.45	296.62	29.57	88.70	83.92	89.91
41	ALLSTON	32.37	96.60	28.00	54.87	55.10	53.85
42	PAUL	24.86	53.63	27.42	43.43	44.91	41.93
43	RAVER	25.07	4.46	44.76	46.36	51.56	42.59
44	SATSOP	13.25	28.45	15.26	23.53	24.47	22.71
45	OLYMPIA	17.80	40.70	19.97	31.41	32.47	30.39
46	TACOMA	15.36	-8.82	29.89	29.21	33.26	26.54
47	COVINGTN	16.89	-7.55	32.64	32.00	36.35	29.10
48	MAPLE VL	15.86	-12.73	32.53	30.25	34.73	27.31
49	ECHOLAKE	18.90	-9.05	37.39	35.67	40.56	32.37
50	MONROE	10.50	-33.06	30.02	20.90	26.01	17.82
51	OSTRANDR	49.58	255.01	30.02	82.75	79.16	83.37
52	TROUTDAL	35.04	178.08	21.50	58.72	56.45	59.10
53	MCLOUGLN	41.90	211.79	25.90	70.32	67.56	70.74
54	SCHULTZ	25.71	-22.75	53.46	48.44	56.01	43.16
55	VANTAGE	34.13	0.12	50.95	66.98	74.10	61.26
56	HANFORD	57.61	93.51	70.22	118.55	124.46	111.01
57	ASHE	58.10	64.15	64.34	120.00	124.88	113.07
58	LOW MON	57.88	4.65	76.41	133.79	143.89	122.55
59	LIT GOOS	39.19	-23.19	77.67	121.30	136.61	77.84
60	LOW GRAN	23.62	-45.25	81.32	70.48	125.09	43.34
61	HATWAI	6.24	-68.97	95.74	18.54	51.22	7.20
62	DWORSHAK	-1.24	-72.82	97.23	-3.69	17.70	-7.89
63	SACJWA T	80.74	30.88	49.95	99.05	103.89	93.39
64	MCNARY	70.24	88.90	41.19	91.69	93.03	88.87
65	TABLE MT	31.93	343.15	9.01	51.12	44.92	53.86
66	VACA-DIX	25.87	296.73	6.14	41.24	35.71	43.75
67	CUSTERW	4.29	-25.04	18.03	9.04	12.19	7.30
68	ING500	3.23	-25.63	16.63	7.03	9.98	5.43
69	TAFT	-9.21	-73.00	135.32	-26.37	-20.03	-23.13
70	GARRISON	-9.25	-60.86	78.48	-26.36	-24.09	-22.29
71	HOT SPR	-6.15	-46.70	121.74	-17.42	-13.92	-15.17
72	BELL	-4.66	-46.91	121.22	-11.67	-6.35	-11.16
77	COULEE	17.86	-68.72	61.24	35.19	45.53	28.66

Table D.1 Continued

FAULT	GEN* KV* EMWS*	MCNARY 1 13.8 1 702	MCNARY 2 13.8 1 2388	NOXON 5 14.4 1 375.6	PELTON 13.8 1 258.9	PRIESTR2 13.8 1 2560	ROCK IS2 6.9 1 951
1	GRIZZLY	78.27	203.99	22.70	58.00	127.09	39.61
7	ALVEY	52.04	133.66	15.80	22.53	89.82	29.33
8	DIXONVLE	43.41	112.79	12.56	22.47	73.16	23.70
10	MERIDINP	39.57	105.72	10.27	26.87	63.75	20.38
11	CPT JAC	64.99	178.26	15.36	60.59	98.64	30.61
13	SUMMER L	51.07	134.91	14.33	40.07	80.30	24.93
15	BURNS	23.67	59.20	8.54	13.57	38.57	12.03
16	MIDPOINT	5.51	7.42	6.54	-4.52	12.56	4.05
18	PONDROSA	60.13	159.21	16.41	49.33	94.80	29.37
20	MALIN	65.96	180.93	15.60	62.09	99.97	31.00
23	OLINDA	34.92	100.08	6.37	42.03	49.65	15.24
24	ROUND MT	50.88	143.72	10.22	57.19	73.81	22.72
28	MARION	70.18	173.70	24.54	22.49	128.84	42.80
30	PEARL	69.27	170.54	24.72	20.73	137.75	47.03
34	KEELER	56.85	135.24	22.30	12.87	118.77	42.68
40	SANTIAM	70.69	177.43	23.61	26.79	127.07	41.96
41	ALLSTON	42.75	94.38	21.71	5.69	103.39	43.17
42	PAUL	32.03	67.20	21.02	2.86	89.99	43.33
43	RAVER	29.10	51.48	33.55	-0.97	119.63	74.88
44	SATSOP	17.37	36.45	11.71	1.64	49.40	24.13
45	OLYMPIA	23.16	49.14	15.35	2.42	65.83	32.38
46	TACOMA	18.15	29.98	22.33	-1.68	76.07	46.42
47	COVINGTN	19.88	33.18	24.38	-1.60	83.43	51.13
48	MAPLE VL	18.61	29.92	24.25	-2.04	79.93	50.62
49	ECHOLAKE	22.08	36.64	27.90	-1.86	93.58	59.09
50	MONROE	12.41	14.82	22.02	-3.54	58.51	37.18
51	OSTRANDR	65.33	159.43	23.81	17.86	133.09	44.19
52	TROUTDAL	47.08	114.27	17.05	12.76	96.99	31.61
53	MCLOUGLN	55.41	133.92	20.51	14.55	113.61	37.71
54	SCHULTZ	28.65	44.49	39.72	-3.19	130.92	72.50
55	VANTAGE	35.16	60.77	38.05	-0.96	176.47	71.09
56	HANFORD	51.08	105.49	52.60	5.02	174.55	69.75
57	ASHE	59.31	112.84	48.29	3.44	155.53	56.19
58	LOW MON	49.04	78.36	56.37	-0.83	115.99	40.43
59	LIT GOOS	35.34	50.27	56.61	-2.75	85.20	29.48
60	LOW GRAN	21.83	20.35	58.29	-4.36	59.11	20.66
61	HATWAI	6.35	-14.81	66.36	-6.23	30.71	11.14
62	DWORSHAK	-0.65	-27.18	64.59	-6.43	15.84	6.08
63	SACJWA T	56.13	101.43	37.39	1.47	98.25	31.29
64	MCNARY	86.51	196.37	31.39	5.86	107.48	32.89
65	TABLE MT	44.30	127.07	8.09	53.60	62.87	19.28
66	VACA-DIX	36.01	105.30	5.75	47.30	49.70	15.18
67	CUSTERW	5.27	4.02	12.85	-2.48	26.77	16.56
68	ING500	4.02	1.71	11.73	-2.49	21.62	13.24
69	TAFT	-8.73	-39.09	77.76	-6.40	-4.38	-1.32
70	GARRISON	-9.03	-35.11	39.28	-5.44	-8.38	-2.96
71	HOT SPR	-5.92	-25.42	65.46	-4.11	-3.79	-1.24
72	BELL	-4.61	-22.59	77.24	-4.12	-2.03	-0.78
77	COULEE	19.68	19.10	44.93	-6.62	101.10	59.44

Table D.1 Continued

FAULT	GEN* KV* EMWS*	ROCKY RH 15.0 1 2366	ROUND BU 13.8 1 1536	WANAPUM 13.8 1 1980	WELLS 14.4 1 2960
1	GRIZZLY	137.84	153.63	217.81	77.98
7	ALVEY	104.13	60.88	155.23	59.00
8	DIXONVLE	84.58	57.07	126.71	47.64
10	MERIDINP	73.17	62.28	111.16	40.71
11	CPT JAC	109.33	135.69	172.34	60.21
13	SUMMER L	88.04	101.66	138.36	49.27
15	BURNS	42.30	40.96	65.42	24.08
16	MIDPOINT	13.77	1.56	19.54	8.54
18	PONDROSA	103.50	125.15	163.25	57.93
20	MALIN	110.68	139.04	174.64	60.95
23	OLINDA	55.32	82.57	88.47	29.70
24	ROUND MT	82.08	116.79	130.55	44.45
28	MARION	148.39	70.22	221.90	85.79
30	PEARL	165.01	64.42	232.71	95.61
34	KEELER	151.31	47.45	200.47	88.45
40	SANTIAM	146.22	76.87	218.52	84.17
41	ALLSTON	154.46	30.73	177.67	92.94
42	PAUL	154.64	21.28	158.98	95.97
43	RAVER	245.75	15.80	227.22	164.79
44	SATSOP	89.19	11.33	86.90	54.90
45	OLYMPIA	118.62	15.34	116.59	72.95
46	TACOMA	158.70	8.91	140.56	106.50
47	COVINGTN	172.69	10.01	154.97	116.29
48	MAPLE VL	171.88	8.94	147.33	116.26
49	ECHOLAKE	197.41	11.11	174.10	133.55
50	MONROE	122.04	4.77	101.43	87.69
51	OSTRANDR	153.87	58.14	223.59	89.17
52	TROUTDAL	110.87	40.80	159.73	64.23
53	MCLOUGLN	131.78	48.63	190.24	76.46
54	SCHULTZ	242.82	14.30	254.54	172.04
55	VANTAGE	202.21	19.63	429.58	132.75
56	HANFORD	213.34	45.40	361.50	135.59
57	ASHE	176.37	35.76	296.32	109.31
58	LOW MON	127.13	22.23	207.05	79.95
59	LIT GOOS	93.13	13.80	146.76	59.25
60	LOW GRAN	65.16	7.09	98.09	42.43
61	HATWAI	34.25	-0.18	45.70	24.06
62	DWORSHAK	17.87	-3.14	19.40	14.01
63	SACJWA T	101.14	21.41	163.25	62.10
64	MCNARY	108.10	31.45	175.16	64.84
65	TABLE MT	70.02	105.43	111.99	37.58
66	VACA-DIX	55.43	89.31	89.40	29.40
67	CUSTERW	56.42	1.43	43.39	41.38
68	ING500	44.55	0.76	33.77	33.64
69	TAFT	-7.23	-6.58	-15.41	-1.15
70	GARRISON	-12.14	-6.44	-20.50	-4.84
71	HOT SPR	-5.96	-4.37	-11.50	-1.56
72	BELL	-5.51	-3.82	-9.16	-0.68
77	COULEE	167.07	7.39	172.83	125.37

Table D.1 Continued

FAULT	GEN- | KV- | EMWS-	BONPH2 13.8 1 1456	BONN1 13.8 1 927	BONN2 13.8 1 1530	BOUND 14.4 1 962	BOUND2 14.4 1 962	BOYLE 11.5 1 223
1	GRIZZLY	219.61	59.80	126.25	32.33	22.08	-16.48
7	ALVEY	180.29	45.05	102.95	20.77	14.18	-10.28
8	DIXONVLE	145.89	36.72	83.02	16.82	11.50	-6.30
10	MERIDINP	122.40	31.54	69.38	13.29	9.14	11.39
11	CPT JAC	170.69	47.10	96.99	21.09	14.53	10.58
13	SUMMER L	127.84	35.33	72.49	18.74	12.85	1.24
15	BURNS	177.04	47.23	102.31	31.58	21.40	-23.82
16	MIDPOINT	33.62	9.08	18.89	9.73	6.63	-1.25
18	PONDROSA	146.12	40.55	83.06	21.45	14.69	-9.68
20	MALIN	172.24	47.64	97.88	21.47	14.80	10.58
23	OLINDA	85.80	24.23	48.43	8.42	5.88	26.51
24	ROUND MT	127.80	35.86	72.28	13.89	9.65	21.46
28	MARION	212.28	50.00	126.59	34.68	23.48	-18.53
30	PEARL	300.09	53.93	178.52	32.17	21.84	-13.14
34	KEELER	338.35	81.94	200.22	33.10	22.44	-8.79
40	SANTIAM	261.16	65.52	153.35	32.48	22.08	-18.51
41	ALLSTON	85.31	10.86	55.32	36.73	24.51	-27.39
42	PAUL	130.03	32.81	75.56	36.45	24.29	-11.04
43	RAVER	73.67	17.17	42.47	57.58	38.38	-11.49
44	SATSOP	70.72	17.58	40.11	20.79	13.88	-5.51
45	OLYMPIA	91.14	22.85	52.12	26.38	17.61	-7.24
46	TACOMA	59.98	13.93	34.08	47.73	31.45	-9.49
47	COVINGTN	57.08	12.96	32.58	51.43	33.89	-10.53
48	MAPLE VL	55.36	12.56	31.62	53.83	35.50	-10.19
49	ECHOLAKE	81.67	19.84	46.59	61.82	40.84	-9.51
50	MONROE	55.34	12.67	31.18	61.82	40.53	-9.08
51	OSTRANDR	367.97	87.80	217.61	33.02	22.45	-8.39
52	TROUTDAL	294.72	49.22	176.47	26.32	17.81	-11.05
53	MCLOUGLN	339.00	66.74	202.03	31.27	21.22	-10.31
54	SCHULTZ	31.05	5.57	17.89	65.56	42.71	-18.07
55	VANTAGE	54.11	12.08	30.97	53.79	35.50	-19.20
56	HANFORD	112.09	26.72	65.36	67.99	45.18	-26.79
57	ASHE	106.41	25.44	61.54	60.00	39.97	-24.57
58	LOW MON	67.03	14.91	38.42	71.81	47.58	-23.27
59	LIT GOOS	40.73	8.18	22.99	72.24	47.72	-18.98
60	LOW GRAN	23.49	4.03	13.02	74.89	49.29	-14.85
61	HATWAI	10.68	1.27	5.74	87.09	57.13	-10.09
62	DWORSHAK	4.65	0.03	2.37	86.75	56.76	-7.60
63	SACJWA T	57.40	13.17	32.55	44.06	29.29	-16.40
64	MCNARY	84.37	21.16	48.16	37.66	25.18	-16.79
65	TABLE MT	110.25	31.17	62.29	11.06	7.72	31.92
66	VACA-DIX	87.42	25.01	49.35	7.68	5.41	33.65
67	CUSTERW	19.69	4.23	10.90	64.61	41.56	-4.01
68	ING500	16.82	3.60	9.29	70.86	45.60	-3.41
69	TAFT	-0.90	-0.95	-0.68	134.04	87.19	-4.69
70	GARRISON	-1.44	-0.88	-0.93	85.78	55.23	-3.47
71	HOT SPR	-0.90	-0.66	-0.62	82.53	53.26	-2.82
72	BELL	-1.52	-0.88	-0.99	187.80	122.23	-3.28
77	COULEE	-4.33	-4.33	-2.18	81.64	52.69	-24.43

Table D.2 Heavy Spring Generation Individual Acceleration Power
Based On System Faults

FAULT	CAB GORG 13.8 1 190.8	CENTR G1 20.0 1 2204	CENTR G2 20.0 1 2204	CHIEF J2 13.8 1 1632	CHIEF J5 13.8 1 3263.7	CHIEF JO 13.8 1 1808	COULEE 2 13.8 1 10314
1	19.00	237.10	236.63	99.42	250.05	104.71	460.82
7	11.74	202.75	202.35	69.61	174.74	73.36	314.20
8	9.59	162.21	161.86	55.75	140.89	58.73	254.30
10	7.72	131.33	131.00	43.59	112.54	45.94	204.02
11	12.67	175.92	175.44	64.56	168.82	68.06	310.40
13	11.47	133.12	132.79	53.40	137.26	56.28	254.70
15	18.44	203.32	203.03	93.92	229.29	98.87	422.84
16	6.81	36.09	36.01	16.49	40.99	17.37	81.32
18	12.90	152.94	152.58	63.33	161.91	66.74	299.68
20	12.93	177.35	176.86	65.44	171.11	69.00	314.83
23	5.17	83.73	83.44	26.58	73.01	28.05	134.12
24	8.47	127.09	126.69	43.00	115.79	45.37	212.89
28	19.12	290.10	289.82	116.80	282.46	122.90	508.64
30	17.19	357.67	357.26	117.40	283.73	123.34	508.79
34	17.03	436.08	435.66	128.44	308.44	135.22	536.14
40	17.98	307.08	306.67	111.27	272.27	117.08	491.04
41	17.15	537.88	537.96	153.09	343.87	160.55	587.30
42	15.36	638.67	639.08	174.92	386.01	183.56	630.48
43	22.09	292.66	293.30	316.41	686.61	329.72	1049.14
44	8.62	356.22	356.51	100.84	223.42	105.91	369.83
45	10.99	451.15	451.60	127.61	282.63	133.90	471.70
46	17.75	222.73	223.53	259.74	532.63	271.17	801.13
47	19.04	201.91	202.85	281.15	574.88	293.33	860.46
48	19.00	198.03	198.91	294.92	597.73	307.62	870.00
49	21.69	308.53	309.15	344.02	702.02	359.20	1021.82
50	18.90	197.53	198.32	327.30	647.88	341.41	859.66
51	17.79	366.88	366.40	120.33	293.59	126.72	522.33
52	14.02	269.82	269.57	95.17	228.23	100.12	407.59
53	16.77	344.80	344.34	113.37	275.63	119.33	490.99
54	28.18	46.74	48.22	342.06	699.80	353.99	1175.17
55	27.22	118.37	118.81	207.42	440.83	216.58	828.63
56	38.13	174.50	174.76	212.42	469.11	222.17	898.71
57	35.19	157.03	157.17	162.72	365.28	170.53	698.77
58	45.95	107.64	107.86	126.73	272.82	132.76	549.53
59	48.13	71.93	72.14	94.00	196.96	98.50	412.94
60	51.54	46.72	46.91	68.75	139.56	72.05	310.64
61	62.29	25.79	25.93	45.89	88.14	48.10	226.63
62	61.99	15.46	15.57	33.97	61.93	35.60	177.32
63	27.72	84.88	84.98	84.81	187.33	89.01	372.37
64	23.16	108.31	108.32	84.04	191.83	88.28	374.47
65	6.79	107.84	107.48	34.70	95.03	36.61	174.63
66	4.77	83.40	83.09	24.69	69.63	26.06	127.85
67	9.84	74.23	74.51	157.93	312.90	165.28	385.88
68	8.97	63.81	64.05	135.15	267.84	141.53	330.21
69	98.19	4.60	4.69	25.10	37.99	26.25	155.64
70	64.23	2.03	2.10	15.72	23.07	16.44	91.80
71	79.43	2.25	2.31	14.82	21.99	15.51	90.01
72	94.99	1.48	1.58	25.52	33.96	26.64	166.76
77	35.91	-69.44	-67.35	395.85	684.75	403.56	1551.68

Table D.2 Continued

FAULT	COULEE51 15.0 1 9132	COULEE52 15.0 1 7160	COULEE52 15.0 2 3580	DALLES 1 13.8 1 1020	DALLES 3 13.8 1 2072	DALLES21 13.8 1 1530	DALLES22 13.8 1 1020
1	451.93	374.61	186.76	166.43	467.91	304.72	203.06
7	309.07	256.44	127.85	94.17	262.02	170.15	113.38
8	249.91	207.37	103.40	80.00	225.09	145.42	96.89
10	200.62	166.37	82.97	72.95	210.54	134.28	89.43
11	305.04	252.86	126.13	129.94	380.69	241.92	161.09
13	248.63	206.21	102.84	101.63	293.06	187.91	125.16
15	412.58	342.45	170.66	130.30	349.19	233.36	155.64
16	74.08	61.53	30.68	25.84	73.19	47.33	31.54
18	293.64	243.56	121.45	118.81	340.17	219.10	145.96
20	309.32	256.41	127.90	132.24	387.46	246.25	163.97
23	132.25	109.41	54.61	67.31	204.68	127.37	84.75
24	209.62	173.59	86.62	100.10	300.33	188.33	125.35
28	497.38	412.48	205.55	124.17	336.06	224.48	149.72
30	491.71	407.17	202.91	121.26	335.27	221.83	147.91
34	519.86	430.71	214.64	119.98	323.52	213.29	142.20
40	479.19	397.08	197.91	129.00	351.11	231.69	154.47
41	555.38	459.66	228.88	43.74	98.46	77.51	51.95
42	600.62	496.66	247.28	45.07	110.17	77.21	51.58
43	1060.09	864.21	430.03	29.91	66.73	49.82	33.35
44	343.52	285.35	142.08	23.88	58.68	40.84	27.28
45	436.94	362.23	180.36	30.85	75.63	52.73	35.22
46	797.98	655.33	326.06	24.15	53.44	40.05	26.81
47	860.35	705.26	350.89	24.02	51.81	39.62	26.54
48	858.41	703.89	350.23	23.50	50.91	38.83	26.01
49	1007.28	824.29	410.23	32.06	74.82	53.88	36.02
50	834.78	684.56	340.56	22.29	48.61	36.73	24.60
51	510.16	422.61	210.63	139.91	372.59	246.57	164.41
52	394.62	327.40	163.14	97.69	263.08	176.20	117.53
53	477.69	395.93	197.32	126.09	342.80	227.22	151.51
54	1273.31	1018.07	505.81	17.08	18.67	23.29	15.78
55	796.33	651.97	324.18	29.13	47.17	42.93	28.89
56	911.97	746.34	371.31	63.95	131.20	101.96	68.33
57	698.08	575.20	286.25	62.59	134.69	101.73	68.12
58	517.61	427.99	212.89	37.55	65.38	56.47	37.95
59	371.46	308.46	153.39	21.62	28.28	29.79	20.12
60	261.68	218.18	108.46	11.59	7.41	13.74	9.36
61	163.86	137.23	68.20	4.63	-3.66	3.60	2.54
62	114.62	96.33	47.85	1.35	-8.74	-1.16	-0.67
63	350.06	290.85	144.73	33.47	66.03	52.72	35.36
64	354.09	294.10	146.42	52.79	119.78	87.78	58.72
65	172.15	142.46	71.10	86.94	263.84	164.41	109.40
66	126.31	104.37	52.11	69.63	214.75	132.63	88.23
67	376.91	312.95	155.67	8.29	17.19	13.46	9.02
68	321.87	267.68	133.15	7.07	14.68	11.49	7.70
69	70.28	59.50	29.51	-1.38	-11.37	-4.65	-3.04
70	42.77	36.39	18.03	-1.46	-9.42	-4.17	-2.74
71	40.66	34.54	17.13	-1.03	-7.38	-3.15	-2.06
72	64.04	54.50	26.99	-1.24	-8.80	-3.74	-2.45
77	1824.72	1369.71	678.76	1.64	-34.82	-7.25	-4.48

Table D.2 Continued

FAULT	DIABLO 13.8 1 570.6	DWOR 3 13.8 1 786	DWOR 1-2 13.8 1 616	ENSERCH1 13.8 1 100	ENSERCH2 13.8 1 100	ENSERCH3 13.8 1 100	ENSERCH4 13.8 1 100
1	17.81	64.38	73.81	4.64	4.64	4.64	5.27
7	13.46	39.59	45.28	3.50	3.50	3.50	3.98
8	10.85	32.64	37.71	2.83	2.83	2.83	3.22
10	8.75	27.12	32.23	2.31	2.31	2.31	2.64
11	12.66	45.01	54.45	3.37	3.37	3.37	3.86
13	9.98	38.49	45.73	2.64	2.64	2.64	3.01
15	16.11	58.92	65.54	4.17	4.17	4.17	4.70
16	2.86	17.77	21.59	0.75	0.75	0.75	0.86
18	11.63	43.99	51.53	3.07	3.07	3.07	3.50
20	12.81	45.84	55.46	3.41	3.41	3.41	3.91
23	5.77	19.87	25.46	1.57	1.57	1.57	1.81
24	8.94	31.44	39.39	2.41	2.41	2.41	2.77
28	21.05	60.97	67.23	5.39	5.39	5.39	6.07
30	21.89	53.32	58.93	5.53	5.53	5.53	6.22
34	25.93	51.24	56.70	6.54	6.54	6.54	7.36
40	20.55	58.20	64.79	5.25	5.25	5.25	5.93
41	29.62	41.06	40.77	7.23	7.23	7.23	7.99
42	34.69	32.90	33.58	8.26	8.26	8.26	9.07
43	72.26	37.98	36.07	13.89	13.89	13.89	15.11
44	20.91	17.84	18.37	5.00	5.00	5.00	5.51
45	25.97	22.91	23.54	6.19	6.19	6.19	6.82
46	44.55	30.07	28.53	9.29	9.29	9.29	9.68
47	51.94	31.95	30.11	10.57	10.57	10.57	11.09
48	64.40	31.43	29.79	13.16	13.16	13.16	13.97
49	87.79	36.51	35.60	17.28	17.28	17.28	18.60
50	73.79	29.58	27.62	17.90	17.90	17.90	18.94
51	23.09	56.03	62.03	5.86	5.86	5.86	6.62
52	17.71	42.62	46.40	4.48	4.48	4.48	5.04
53	21.72	52.33	57.87	5.53	5.53	5.53	6.23
54	10.05	43.53	35.29	2.87	2.87	2.87	2.19
55	21.34	60.31	51.01	4.81	4.81	4.81	5.10
56	23.29	103.90	92.05	5.53	5.53	5.53	6.00
57	19.10	104.76	94.98	4.63	4.63	4.63	5.07
58	13.65	144.47	118.23	3.23	3.23	3.23	3.49
59	9.52	153.56	117.71	2.22	2.22	2.22	2.38
60	6.49	165.58	114.88	1.50	1.50	1.50	1.59
61	3.87	201.86	116.23	0.90	0.90	0.90	0.94
62	2.54	222.58	108.69	0.58	0.58	0.58	0.60
63	9.94	88.56	78.02	2.41	2.41	2.41	2.63
64	11.10	74.13	70.98	2.75	2.75	2.75	3.05
65	7.47	25.93	33.13	2.03	2.03	2.03	2.34
66	5.64	19.15	25.26	1.55	1.55	1.55	1.79
67	34.67	13.14	11.86	16.43	16.43	16.43	16.30
68	30.68	11.39	10.21	19.57	19.57	19.57	20.43
69	1.17	72.39	21.87	0.28	0.28	0.28	0.26
70	0.63	41.50	6.68	0.14	0.14	0.14	0.12
71	0.64	39.04	9.31	0.15	0.15	0.15	0.13
72	0.75	38.01	8.62	0.18	0.18	0.18	0.14
77	-4.32	41.05	25.23	-2.91	-2.91	-2.91	-4.76

Table D.2 Continued

FAULT	HUNGRY H 13.8 1 2096	ICE H1-2 13.8 1 620	ICE H3-4 13.8 1 310	ICE H3-4 13.8 2 371	ICE H5-6 13.8 1 742	JOHN DAY 13.8 1 7856	LIBBY 13.8 1 2680
1	30.85	57.74	40.56	67.10	81.66	1844.21	37.24
7	18.69	35.03	24.24	40.35	49.91	928.62	22.84
8	15.42	29.13	20.23	33.79	41.49	802.60	18.64
10	12.75	24.88	17.51	29.41	35.58	747.70	14.97
11	21.63	41.73	29.80	50.00	59.76	1429.72	24.75
13	19.57	33.79	23.83	39.88	48.22	1120.53	22.63
15	29.57	49.83	34.04	55.88	69.80	1416.36	36.44
16	12.78	10.68	7.07	11.84	15.20	279.15	14.07
18	21.52	39.47	27.87	46.51	56.19	1318.32	25.35
20	22.10	42.44	30.31	50.84	60.76	1457.65	25.27
23	9.28	19.60	14.28	24.21	28.36	733.26	9.97
24	14.91	30.21	21.84	36.90	43.56	1096.35	16.43
28	29.46	51.97	35.34	58.02	72.73	1270.81	37.34
30	25.93	46.27	30.86	50.86	64.31	1121.83	33.22
34	25.35	45.53	29.90	49.30	64.60	1046.06	32.82
40	27.78	50.56	34.41	56.72	70.93	1254.83	34.95
41	23.17	31.39	18.81	30.29	41.75	493.48	33.06
42	19.72	25.16	15.35	25.07	34.93	412.58	29.04
43	25.60	24.60	14.27	22.92	33.06	292.51	40.92
44	10.95	13.58	8.25	13.59	18.95	217.72	16.21
45	13.98	17.48	10.62	17.45	24.28	281.81	20.68
46	20.65	19.45	11.27	18.17	26.51	232.67	33.17
47	22.07	20.44	11.77	18.91	27.70	235.38	35.57
48	21.97	20.17	11.60	18.67	27.30	231.30	35.46
49	25.36	24.38	14.26	23.05	33.47	302.06	40.40
50	21.32	18.36	10.60	17.05	25.12	213.57	35.24
51	26.99	49.11	32.72	53.92	69.53	1190.79	34.42
52	20.97	37.01	24.05	39.61	51.84	851.65	27.19
53	25.43	46.08	30.45	50.19	64.88	1103.41	32.49
54	31.03	22.38	11.83	17.97	28.71	170.57	52.95
55	34.13	33.92	18.77	28.48	43.39	278.61	52.66
56	52.20	55.72	36.84	56.02	73.04	603.87	75.02
57	50.23	55.19	38.72	59.46	73.20	611.19	69.93
58	65.84	53.90	39.84	57.43	68.99	354.15	92.78
59	68.74	36.39	25.47	36.92	46.59	201.10	97.91
60	72.86	23.29	15.10	21.80	29.63	105.65	105.44
61	86.51	12.45	7.16	10.18	15.53	41.00	127.38
62	90.39	6.95	3.42	4.55	8.41	9.39	130.01
63	40.65	66.89	59.31	85.94	86.63	330.98	55.99
64	34.44	75.60	51.03	78.34	99.80	536.77	46.35
65	12.17	25.46	18.53	31.40	36.82	950.22	13.11
66	8.83	19.49	14.34	24.39	28.30	759.41	9.14
67	10.44	7.64	4.34	7.03	10.43	81.60	18.64
68	9.34	6.53	3.71	6.01	8.93	69.63	17.08
69	132.57	1.58	0.03	-0.51	1.48	-16.15	205.89
70	87.60	0.56	-0.38	-1.01	0.27	-16.30	142.13
71	137.96	0.71	-0.14	-0.56	0.57	-11.57	186.39
72	80.16	0.63	-0.16	-0.62	0.34	-13.00	167.39
77	34.46	13.81	5.66	7.21	15.43	18.91	66.31

Table D.2 Continued

FAULT	LIT GOOS 13.8 1 2946	LOW GRAN 13.8 1 2946	LOW MON 13.8 1 2946	MCNARY 1 13.8 1 702	MCNARY 2 13.8 1 2388	MCNARY 2 13.8 2 2388	NOXON 14.4 1 1128
1	391.21	338.29	429.52	72.39	270.32	270.32	36.49
7	243.38	210.69	267.48	43.85	162.23	162.23	22.36
8	201.83	173.86	222.13	36.77	136.71	136.71	18.20
10	171.21	145.60	189.38	32.22	121.24	121.24	14.48
11	282.21	239.37	312.33	54.87	208.14	208.14	23.84
13	228.29	197.39	250.35	43.69	164.10	164.10	21.96
15	337.82	299.49	366.29	59.80	218.60	218.60	35.98
16	72.75	69.95	74.97	13.67	50.16	50.16	13.67
18	266.40	229.68	292.77	50.58	189.68	189.68	24.69
20	286.81	243.39	317.33	55.80	211.67	211.67	24.33
23	131.66	108.58	147.34	26.99	104.11	104.11	9.37
24	203.34	169.73	226.50	40.90	156.74	156.74	15.61
28	363.35	318.60	396.49	61.29	223.36	223.36	36.93
30	318.80	277.98	348.17	54.34	199.79	199.79	32.84
34	302.50	266.87	329.90	54.97	199.09	199.09	32.46
40	351.18	305.92	384.23	60.95	224.44	224.44	34.49
41	212.12	196.86	224.03	30.09	101.45	101.45	33.29
42	170.60	158.43	181.29	25.71	88.37	88.37	29.20
43	178.30	171.66	185.37	20.11	66.66	66.66	41.63
44	92.23	85.64	98.04	13.86	47.64	47.64	16.26
45	118.66	109.95	126.16	17.80	61.35	61.35	20.75
46	139.70	135.86	145.00	16.33	53.44	53.44	33.77
47	147.26	143.65	152.49	16.74	54.39	54.39	36.24
48	144.96	140.97	150.25	16.48	53.66	53.66	36.04
49	173.04	166.04	180.82	20.91	69.46	69.46	40.87
50	133.18	131.26	137.47	15.16	49.14	49.14	35.88
51	334.70	293.78	365.55	58.91	214.55	214.55	34.03
52	249.03	220.57	270.59	42.78	153.48	153.48	26.97
53	311.38	273.40	339.81	54.75	198.96	198.96	32.12
54	173.03	183.61	170.65	13.94	39.97	39.97	55.17
55	270.47	273.52	273.33	21.10	64.83	64.83	54.60
56	522.20	497.08	542.31	43.30	139.37	139.37	77.21
57	547.20	512.97	573.49	45.66	149.56	149.56	71.74
58	724.78	687.25	747.54	35.53	104.33	104.33	96.47
59	745.05	715.60	472.30	22.03	58.50	58.50	102.50
60	458.90	757.86	287.71	12.61	28.29	28.29	111.19
61	228.37	406.41	142.31	5.33	7.04	7.04	135.39
62	126.25	246.89	75.68	1.83	-2.64	-2.64	136.20
63	451.50	431.78	468.86	44.58	138.89	138.89	57.77
64	389.56	364.59	410.82	73.89	282.33	282.33	47.40
65	171.01	141.35	191.22	34.98	134.81	134.81	12.35
66	130.44	106.09	146.77	27.37	106.45	106.45	8.48
67	56.23	56.38	57.62	6.06	19.31	19.31	18.79
68	48.11	48.37	49.27	5.18	16.50	16.50	17.10
69	27.22	77.87	12.61	-1.17	-9.34	-9.34	214.64
70	10.20	42.27	2.56	-1.31	-8.28	-8.28	148.40
71	12.76	42.02	5.08	-0.91	-6.30	-6.30	190.41
72	15.12	44.53	6.87	-1.14	-7.17	-7.17	183.42
77	118.92	150.07	103.78	4.06	2.36	2.36	70.95

Table D.2 Continued

FAULT	NOXON 5 14.4 1 375.6	PELTON 13.8 1 258.9	PRIEST R 13.8 1 640	PRIESTR2 13.8 1 2560	ROCK IS2 6.9 1 951	ROCKY RH 15.0 1 2366	ROSS 42 13.8 1 1150
1	14.00	56.51	47.35	175.29	49.43	168.95	11.40
7	8.60	20.45	30.67	113.24	33.64	118.18	8.63
8	7.02	20.21	25.09	92.56	27.24	95.53	7.06
10	5.64	23.71	20.76	76.38	21.92	77.04	5.93
11	9.33	54.72	33.06	121.67	33.49	116.27	8.79
13	8.50	41.26	26.79	98.92	27.30	93.84	6.72
15	13.65	35.06	42.03	156.38	45.34	153.03	9.71
16	5.21	9.46	7.95	29.39	8.22	27.83	1.85
18	9.53	47.46	31.53	116.55	32.21	110.33	7.74
20	9.52	56.19	33.57	123.54	33.97	117.85	8.90
23	3.78	34.48	14.98	54.81	14.60	51.41	4.33
24	6.21	48.61	23.36	85.70	23.09	80.83	6.52
28	14.00	20.91	47.40	175.87	54.41	187.57	12.33
30	12.45	19.66	45.09	167.62	53.45	187.88	12.71
34	12.33	18.15	45.84	171.21	56.77	205.75	15.11
40	13.12	24.21	46.04	170.75	52.18	181.71	12.37
41	12.26	-1.62	37.25	138.53	60.30	220.43	14.43
42	10.80	3.37	34.13	125.17	64.31	245.60	15.49
43	15.15	0.51	45.60	163.28	110.14	424.31	39.54
44	6.02	1.92	18.98	69.36	36.81	143.80	9.73
45	7.68	2.44	24.25	88.68	46.77	181.17	12.00
46	12.26	0.31	35.11	126.59	86.81	328.54	8.01
47	13.14	-0.11	37.44	134.92	93.92	353.06	12.40
48	13.08	-0.06	36.98	133.24	94.82	359.79	20.93
49	14.93	1.55	44.13	158.51	112.82	432.14	38.13
50	12.98	0.13	33.96	123.02	89.33	336.41	24.01
51	12.94	19.72	48.89	182.71	55.70	196.81	13.91
52	10.19	11.46	37.79	142.39	43.48	151.96	10.19
53	12.20	18.31	45.69	171.07	52.38	184.45	12.99
54	19.54	-4.56	47.81	173.50	113.86	377.60	-18.62
55	19.55	-3.41	80.08	274.68	107.43	294.94	5.95
56	27.92	-1.46	73.45	261.60	94.86	285.20	9.07
57	26.06	-0.14	58.82	211.70	72.94	225.81	8.25
58	34.50	-4.02	43.42	159.96	54.51	165.95	4.88
59	36.35	-4.69	30.18	111.94	38.88	118.16	2.93
60	39.05	-4.54	20.43	76.32	27.15	82.28	1.64
61	47.08	-3.63	11.99	45.26	16.72	50.36	0.70
62	47.02	-3.10	7.66	29.28	11.43	34.11	0.22
63	20.88	-1.58	33.12	124.96	37.82	117.36	4.14
64	17.35	1.48	36.39	138.15	39.20	123.81	5.39
65	4.97	44.46	19.46	71.25	19.00	66.83	5.59
66	3.48	38.01	14.62	53.36	13.99	49.58	4.39
67	6.70	-0.19	14.58	52.84	37.95	148.27	9.48
68	6.08	-0.16	12.46	45.17	32.40	127.05	9.07
69	71.80	-2.31	3.26	13.09	6.37	18.00	-0.42
70	48.90	-1.80	1.84	7.52	3.83	10.59	-0.41
71	63.42	-1.42	1.79	7.27	3.64	10.21	-0.31
72	60.71	-1.63	2.23	9.27	5.35	14.10	-0.83
77	24.39	-9.76	31.34	122.58	88.92	239.71	-37.70

Table D.2 Continued

FAULT	ROSS 44	ROUND BU	RRCH8-11	TENASKA1	TENASKA2	TENASKA3	TEXWEST1
	13.8 1	13.8 1	15.0 1	13.8 1	13.8 1	13.8 1	13.8 1
	1150	1536	1536	100	100	100	100
1	11.37	220.84	104.58	8.68	8.68	8.66	5.73
7	8.60	78.45	73.17	6.54	6.54	6.52	4.34
8	7.04	75.85	58.96	5.30	5.30	5.28	3.54
10	5.94	86.05	47.18	4.32	4.32	4.31	2.96
11	8.81	199.41	70.94	6.30	6.30	6.29	4.37
13	6.72	154.06	57.60	4.94	4.94	4.93	3.36
15	9.64	149.85	95.69	7.79	7.79	7.76	4.99
16	1.84	35.67	17.20	1.41	1.41	1.41	0.94
18	7.73	180.02	67.87	5.74	5.74	5.72	3.88
20	8.91	204.86	71.91	6.38	6.38	6.37	4.42
23	4.36	119.43	30.86	2.93	2.93	2.93	2.12
24	6.55	171.25	48.84	4.50	4.50	4.50	3.21
28	12.23	85.50	117.57	10.08	10.08	10.04	6.35
30	12.62	77.39	117.44	10.34	10.34	10.31	6.39
34	14.99	72.35	129.17	12.23	12.23	12.19	7.67
40	12.29	94.47	113.41	9.82	9.82	9.79	6.25
41	14.15	5.54	141.20	13.51	13.51	13.43	7.59
42	15.09	17.61	158.61	15.45	15.45	15.34	8.30
43	39.42	7.29	275.66	25.95	25.95	25.75	13.06
44	9.49	9.58	92.31	9.34	9.34	9.29	5.17
45	11.71	12.27	116.32	11.58	11.58	11.51	6.32
46	6.90	5.65	216.86	17.46	17.46	17.25	5.38
47	11.34	4.56	233.07	19.78	19.78	19.55	6.92
48	20.06	4.56	236.66	24.58	24.58	24.33	9.96
49	37.59	10.30	282.32	31.95	31.95	31.67	16.30
50	23.03	4.90	223.04	33.53	33.53	33.17	13.74
51	13.82	78.43	123.14	10.96	10.96	10.93	7.00
52	10.09	48.13	95.45	8.38	8.38	8.35	5.22
53	12.91	73.21	115.37	10.33	10.33	10.30	6.57
54	-20.21	-8.05	262.72	5.57	5.57	5.35	-3.96
55	5.48	-2.78	198.67	8.99	8.99	8.90	3.70
56	8.71	8.84	187.69	10.34	10.34	10.26	5.10
57	7.99	12.31	147.16	8.66	8.66	8.60	4.55
58	4.63	-2.71	109.76	6.04	6.04	5.99	2.87
59	2.72	-7.58	78.84	4.16	4.16	4.12	1.83
60	1.47	-9.19	55.42	2.81	2.81	2.78	1.12
61	0.59	-8.30	34.35	1.68	1.68	1.66	0.58
62	0.13	-7.62	23.61	1.10	1.10	1.09	0.30
63	3.99	2.74	76.66	4.51	4.51	4.48	2.34
64	5.27	14.54	79.69	5.15	5.15	5.12	2.91
65	5.62	154.52	40.15	3.79	3.79	3.78	2.74
66	4.42	129.96	29.52	2.89	2.89	2.89	2.14
67	8.76	1.20	98.01	32.94	32.94	32.39	-0.13
68	8.46	1.03	83.90	38.45	38.45	37.98	11.70
69	-0.50	-6.18	13.20	0.53	0.53	0.51	-0.04
70	-0.47	-4.91	7.99	0.26	0.26	0.26	-0.09
71	-0.36	-3.81	7.59	0.28	0.28	0.28	-0.05
72	-0.91	-4.38	11.02	0.35	0.35	0.34	-0.22
77	-40.03	-24.20	182.61	-5.13	-5.13	-5.39	-14.33

Table D.2 Continued

FAULT	GEN- / KV- / EMWS-	TEXWEST2 13.8 1 100	TEXWEST3 13.8 1 100	TEXWEST4 13.8 1 100	WANAPUM 13.8 1 1980	WANAPUM 13.8 1 660	WELLS 14.4 1 2690
1	GRIZZLY	5.73	5.85	3.84	167.37	111.44	112.49
7	ALVEY	4.34	4.43	2.92	108.88	72.49	78.59
8	DIXONVLE	3.54	3.62	2.39	89.40	59.53	63.07
10	MERIDINP	2.96	3.02	2.03	74.56	49.65	49.82
11	CPT JAC	4.37	4.47	3.02	118.70	79.05	74.40
13	SUMMER L	3.36	3.44	2.30	95.38	63.51	61.06
15	BURNS	4.99	5.09	3.27	146.41	97.47	104.80
16	MIDPOINT	0.94	0.96	0.63	28.10	18.71	18.51
18	PONDROSA	3.88	3.96	2.64	111.90	74.51	72.24
20	MALIN	4.42	4.53	3.05	120.49	80.24	75.42
23	OLINDA	2.12	2.18	1.51	54.78	36.49	31.40
24	ROUND MT	3.21	3.29	2.26	84.78	56.47	50.29
28	MARION	6.35	6.47	4.11	166.60	110.91	129.31
30	PEARL	6.39	6.50	4.10	158.53	105.54	129.14
34	KEELER	7.67	7.81	4.95	158.00	105.18	141.87
40	SANTIAM	6.25	6.37	4.09	162.18	107.97	123.82
41	ALLSTON	7.59	7.67	4.49	130.94	87.12	161.65
42	PAUL	8.30	8.35	4.69	122.53	81.53	182.73
43	RAVER	13.06	13.10	6.94	175.07	116.44	323.30
44	SATSOP	5.17	5.22	3.00	68.37	45.49	105.58
45	OLYMPIA	6.32	6.37	3.63	87.59	58.28	133.30
46	TACOMA	5.38	5.14	1.01	131.04	87.15	259.06
47	COVINGTN	6.92	6.70	1.91	140.33	93.33	278.75
48	MAPLE VL	9.96	9.78	3.82	138.73	92.27	282.05
49	ECHOLAKE	16.30	16.25	8.07	166.74	110.92	331.52
50	MONROE	13.74	13.52	5.56	125.03	83.14	268.48
51	OSTRANDR	7.00	7.14	4.58	168.54	112.20	134.40
52	TROUTDAL	5.22	5.31	3.35	127.63	84.96	105.29
53	MCLOUGLN	6.57	6.69	4.28	156.86	104.42	126.19
54	SCHULTZ	-3.96	-4.46	-5.63	180.42	119.87	342.61
55	VANTAGE	3.70	3.65	1.47	359.32	238.86	244.15
56	HANFORD	5.10	5.11	2.65	291.07	193.58	223.51
57	ASHE	4.55	4.57	2.53	224.21	149.14	172.56
58	LOW MON	2.87	2.86	1.43	155.80	103.59	131.68
59	LIT GOOS	1.83	1.81	0.82	105.12	69.87	95.83
60	LOW GRAN	1.12	1.10	0.43	68.96	45.82	68.30
61	HATWAI	0.58	0.56	0.16	38.75	25.73	43.10
62	DWORSHAK	0.30	0.28	0.02	23.52	15.61	30.23
63	SACJWA T	2.34	2.35	1.28	111.26	73.99	90.18
64	MCNARY	2.91	2.94	1.73	120.68	80.28	91.57
65	TABLE MT	2.74	2.81	1.94	71.09	47.35	40.92
66	VACA-DIX	2.14	2.20	1.53	53.99	35.97	29.56
67	CUSTERW	-0.13	-0.83	-5.11	52.76	35.08	118.05
68	ING500	11.70	11.49	4.50	45.02	29.94	100.91
69	TAFT	-0.04	-0.06	-0.18	8.21	5.43	17.95
70	GARRISON	-0.09	-0.11	-0.17	4.12	2.72	11.12
71	HOT SPR	-0.05	-0.06	-0.13	4.26	2.82	10.42
72	BELL	-0.22	-0.24	-0.32	4.74	3.13	15.44
77	COULEE	-14.33	-15.20	-13.80	98.32	65.15	264.82

Table D.2 Continued

Appendix D Plots of Generator Variation from Average

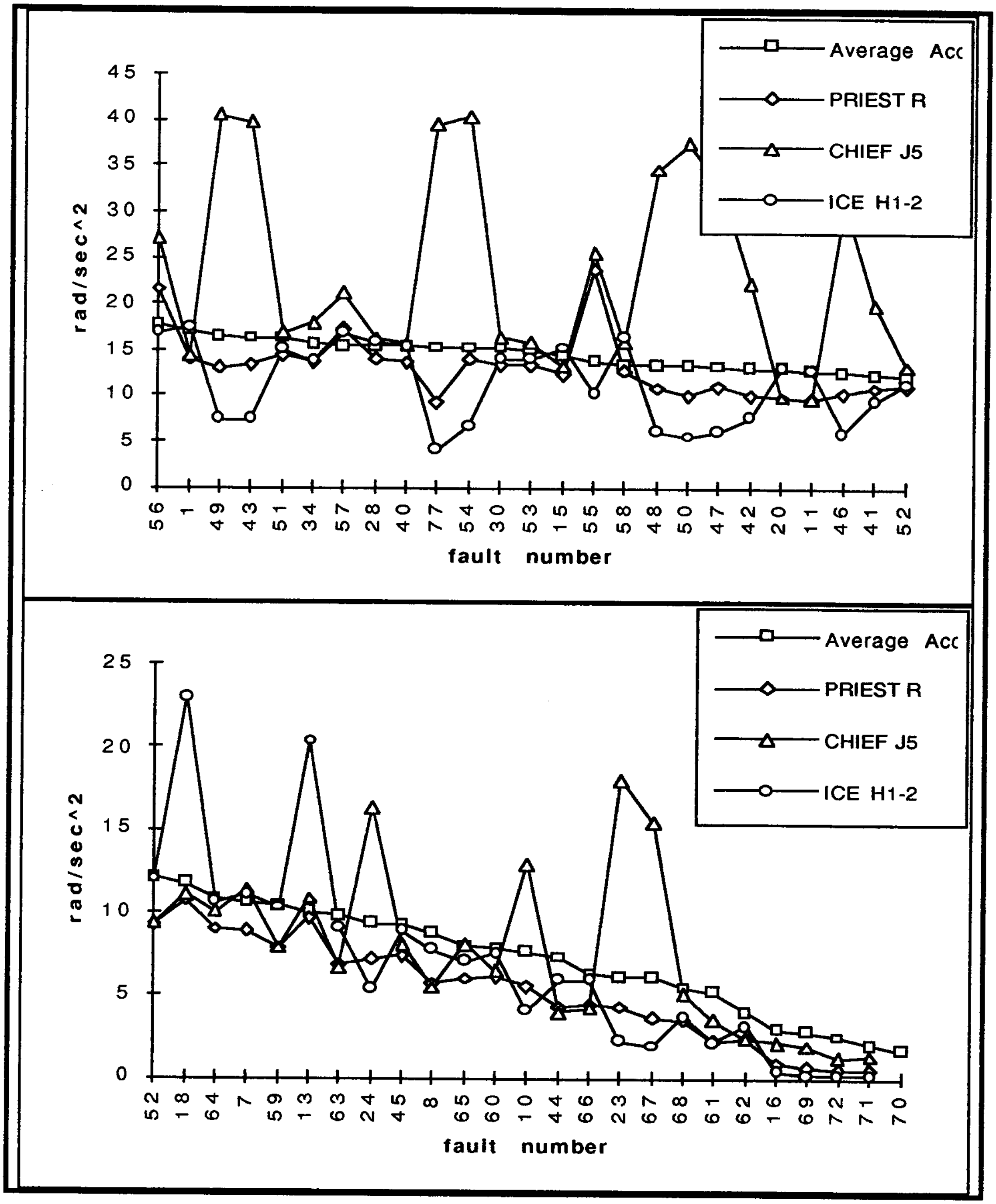

Figure D.1 Comparison of Heavy Spring Generation Acceleration
vs. the Average System Acceleration

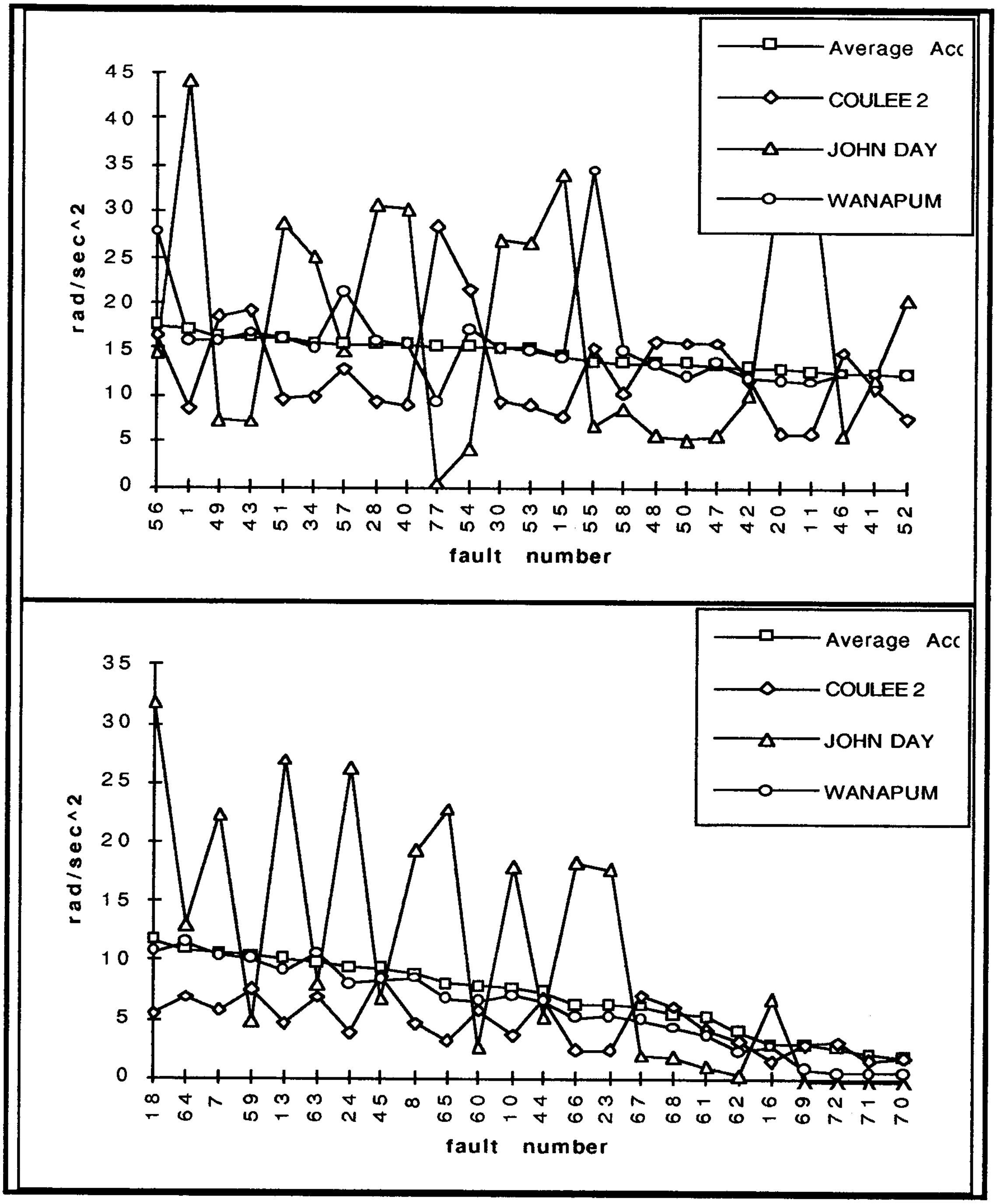

Figure D.2 Comparison of Heavy Spring Generation Acceleration
vs. the Average System Acceleration

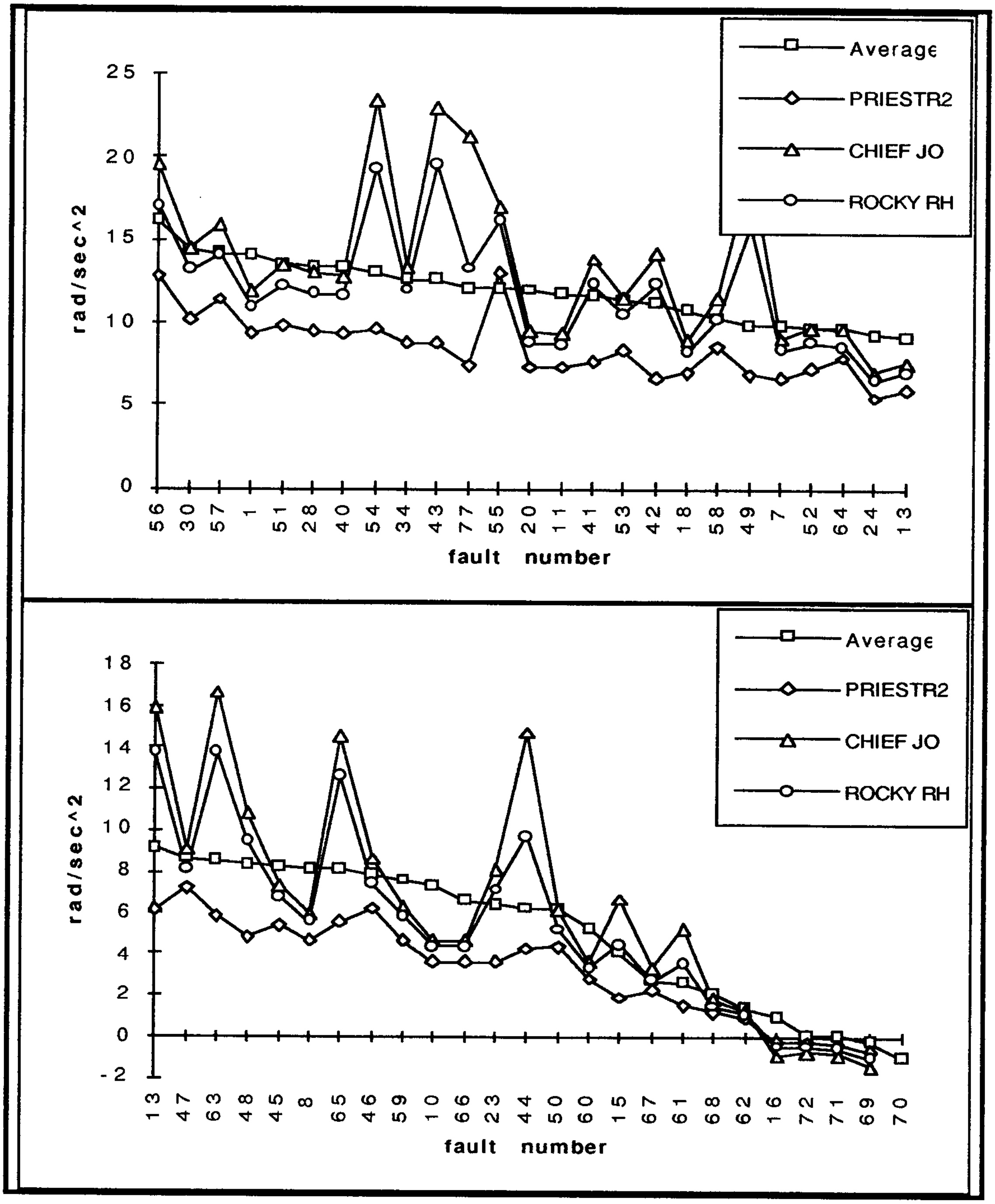

Figure D.3 Comparison of Light Autumn Generation Acceleration vs. the Average System Acceleration

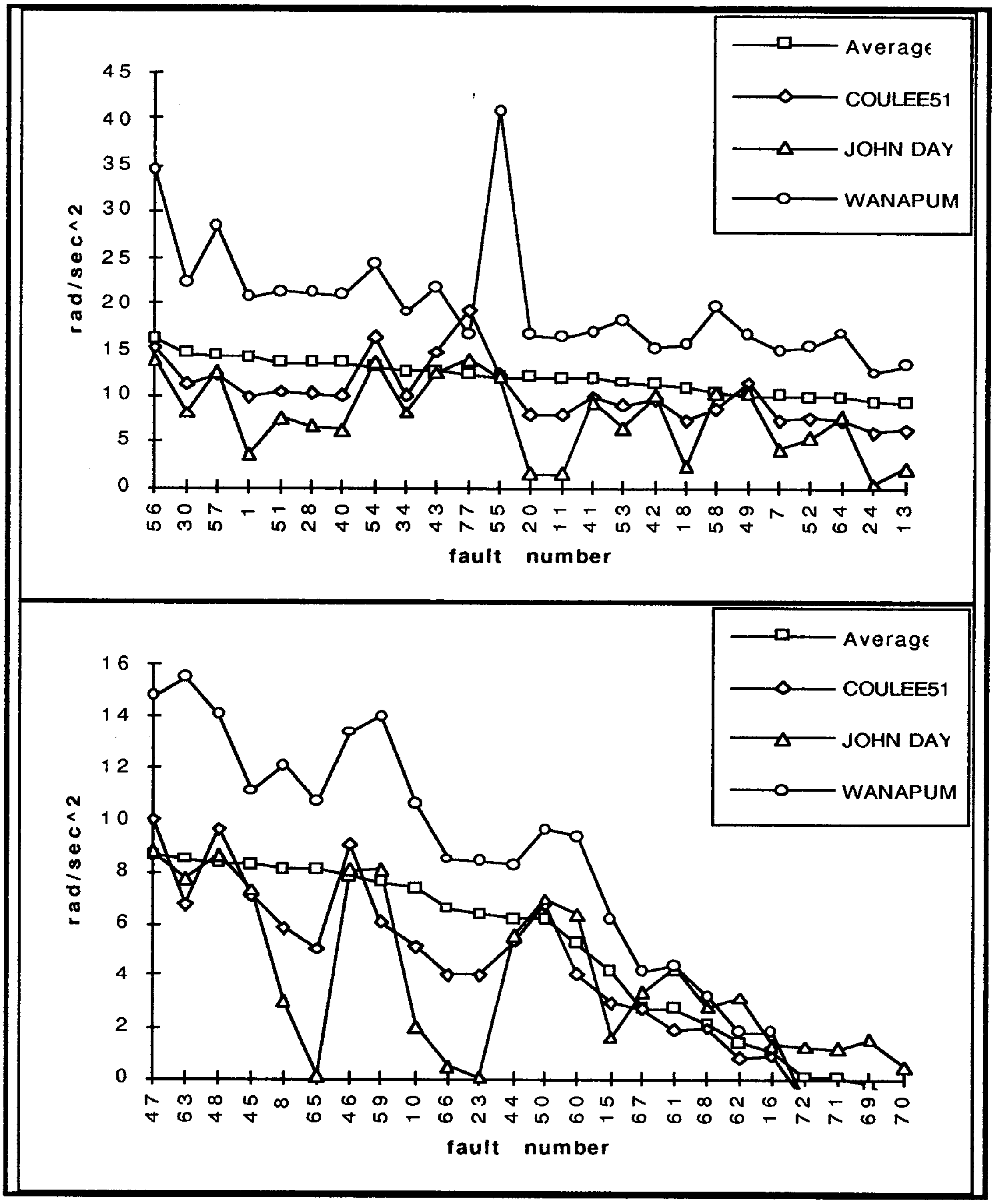

Figure D.4 Comparison of Light Autumn Generation Acceleration vs. the Average System Acceleration

Appendix E 5-Generator Light Spring Model Fault Studies

Three-Phase Circuit Breaker Switched Braking

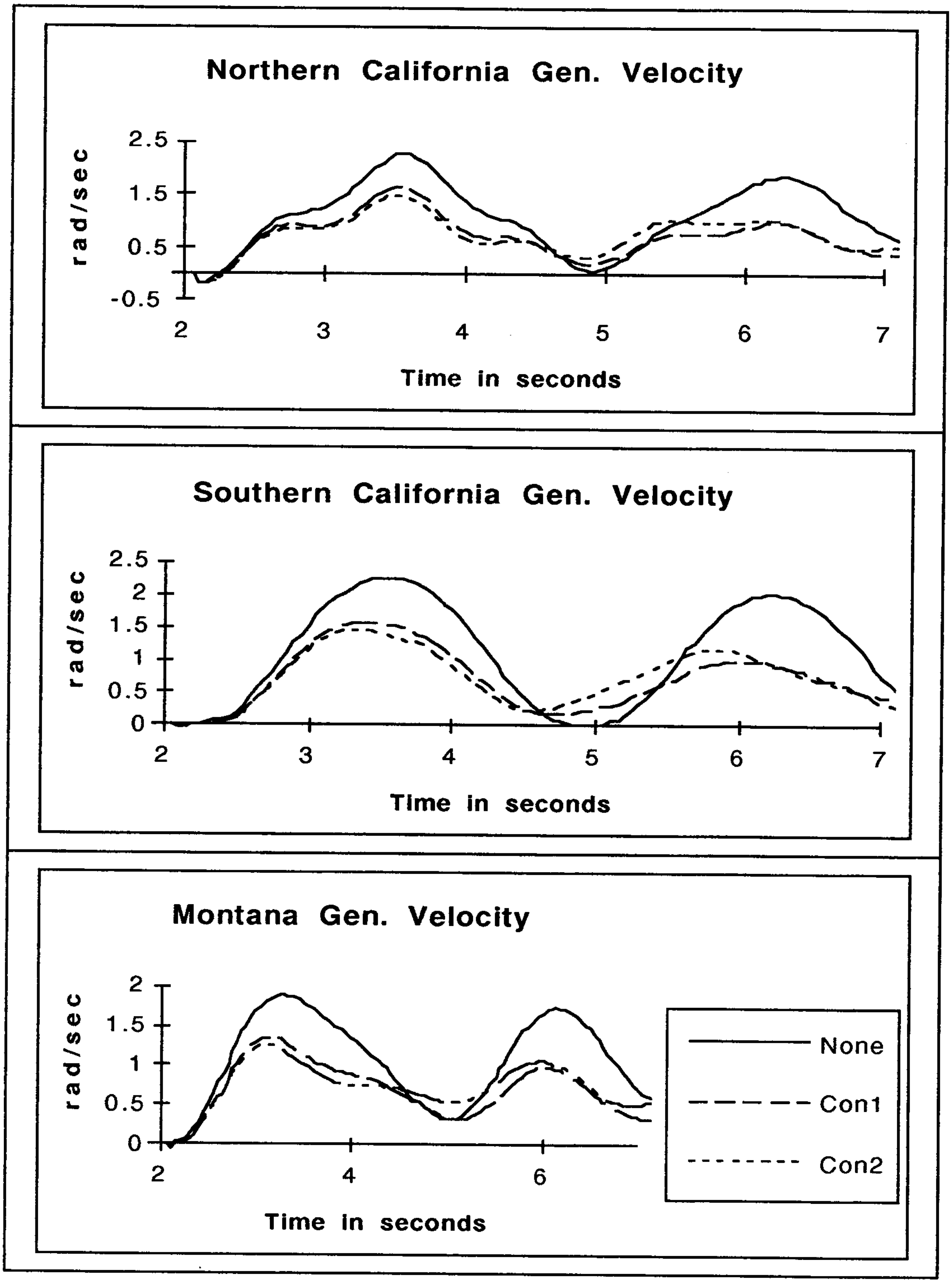

Figure E.1 Relative Generator Velocities for John-Day-Chief Joseph Fault

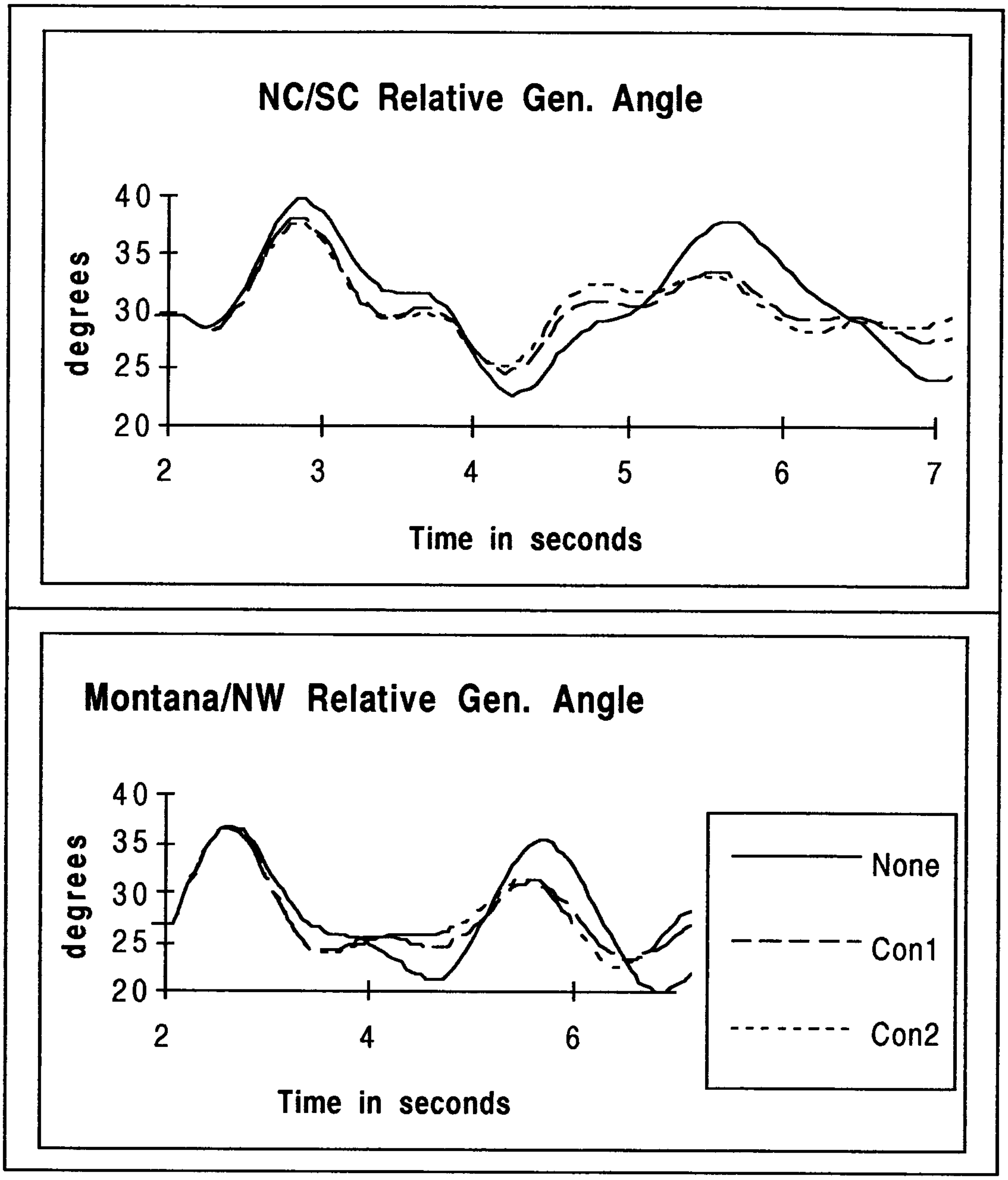

Figure E.2 Relative Generator Swing Angles for John-Day-Chief Joseph Fault

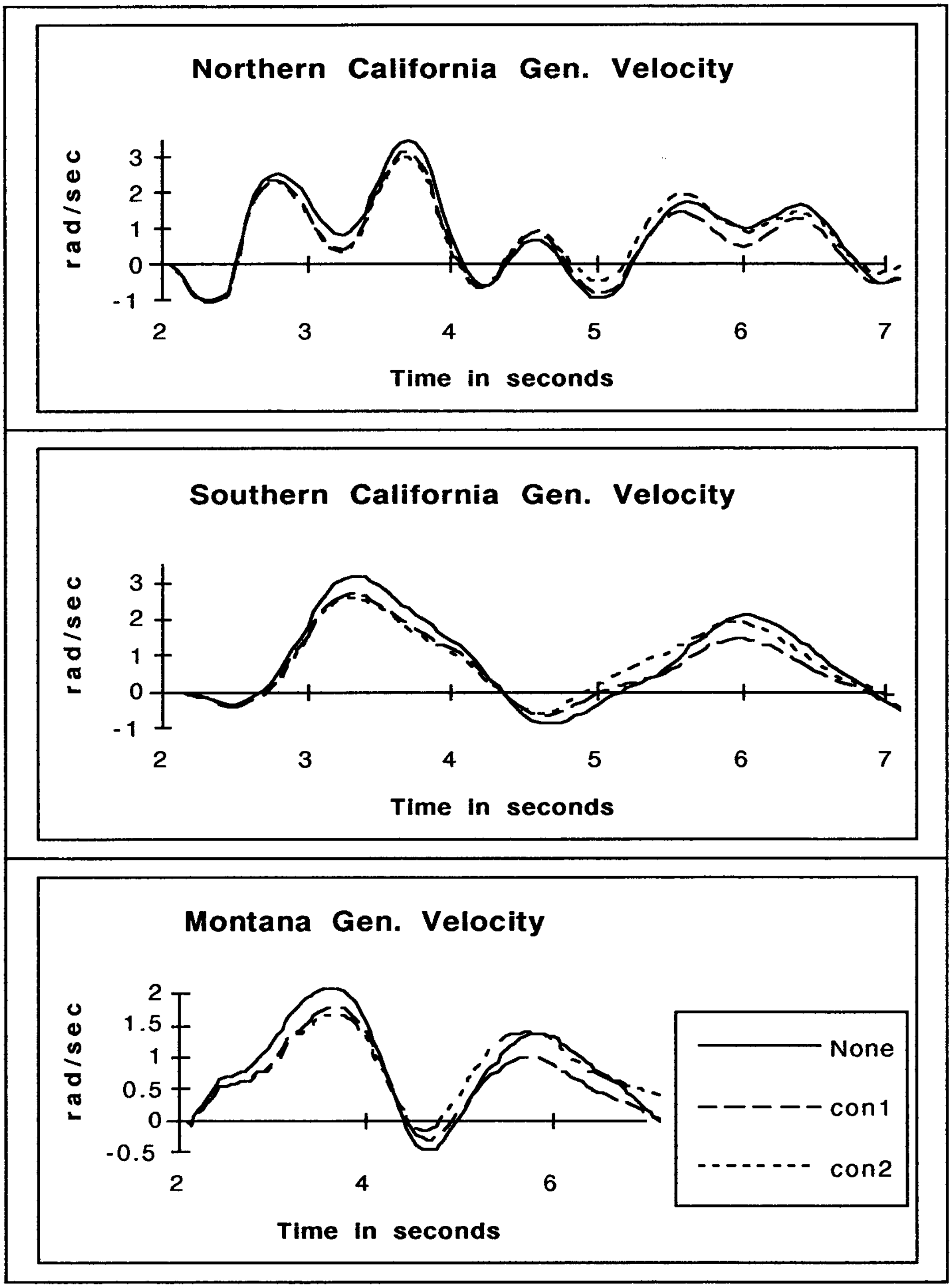

Figure E.3 Relative Generator Velocities for John-Day-Northern California AC Intertie Fault

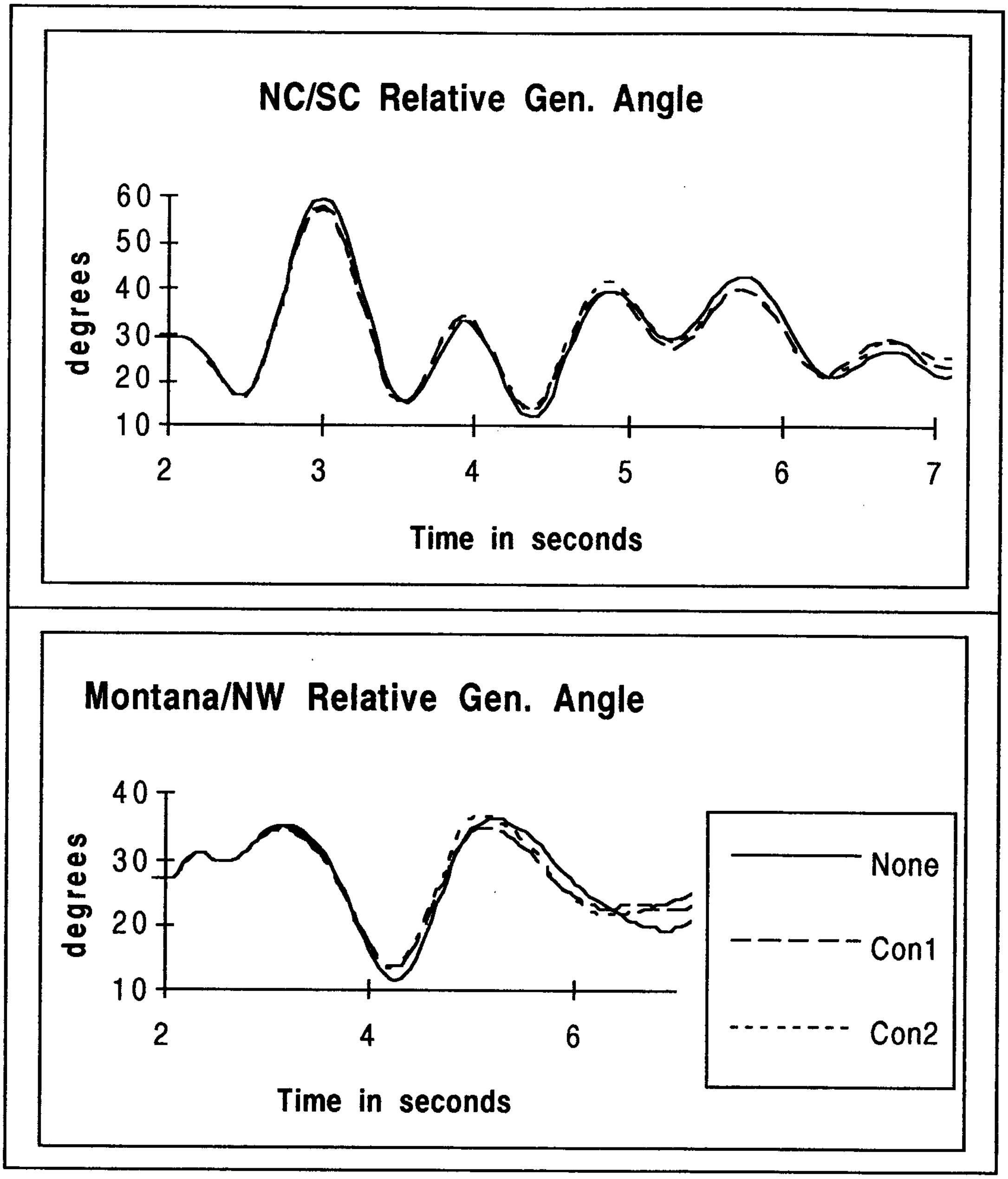

Figure E.4 Relative Generator Swing Angles for John-Day-Northern California AC Intertie Fault

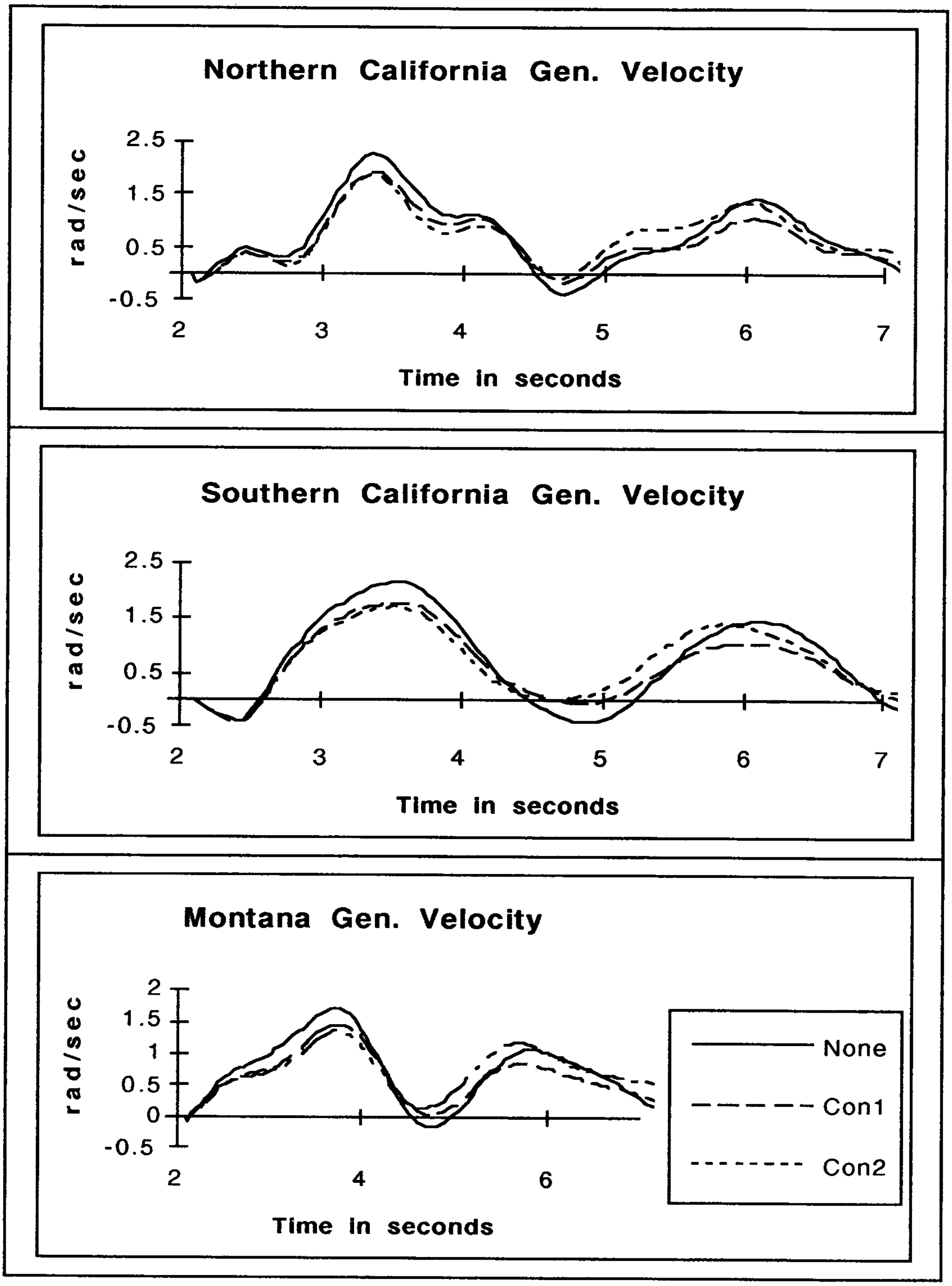

Figure E.5 Relative Generator Velocities for John-Day-Southern California 3rd AC Intertie Fault

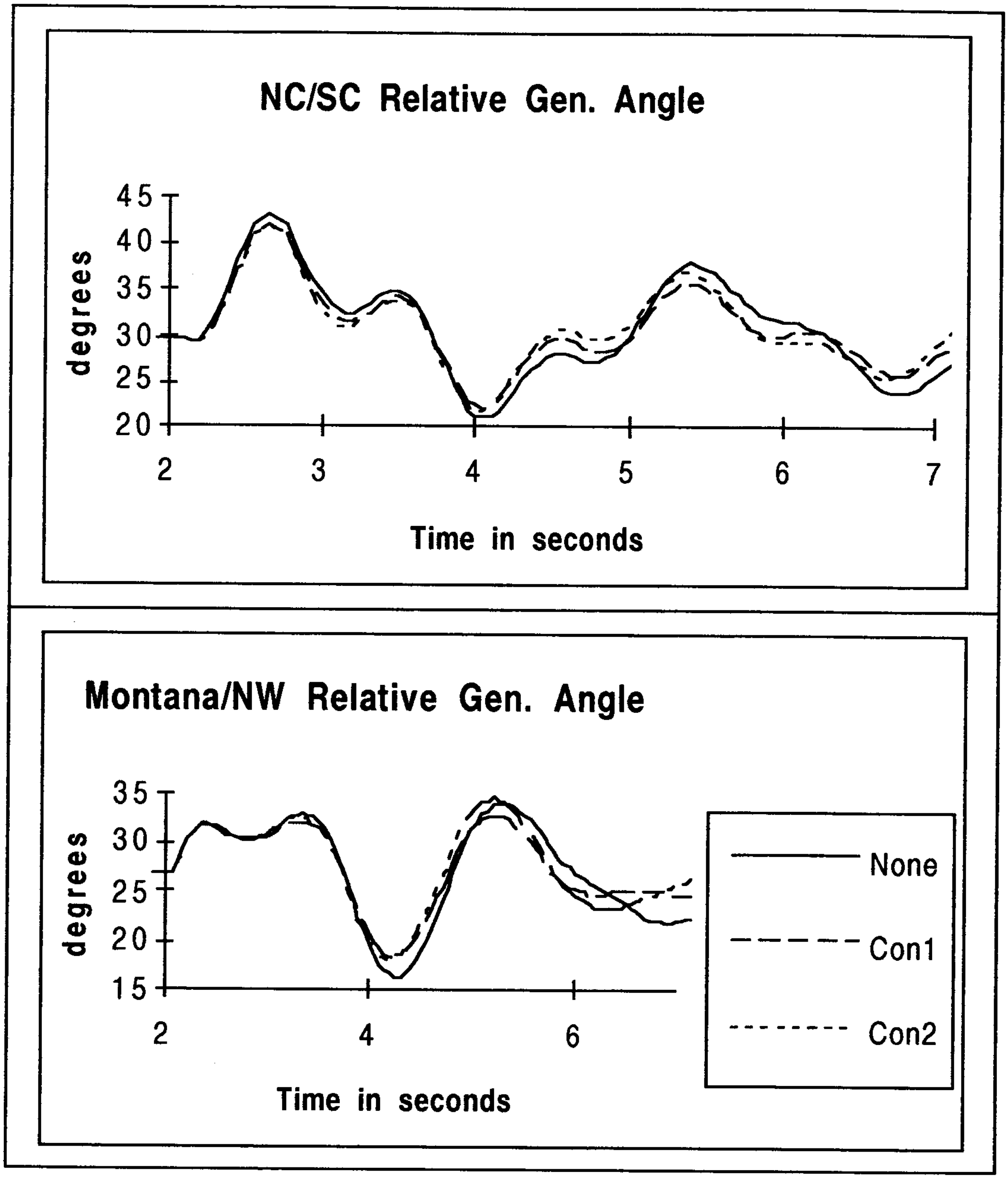

Figure E.6 Relative Generator Swing Angles for John-Day-Southern California 3rd AC Intertie Fault

Single-Phase Circuit Breaker Switched Braking

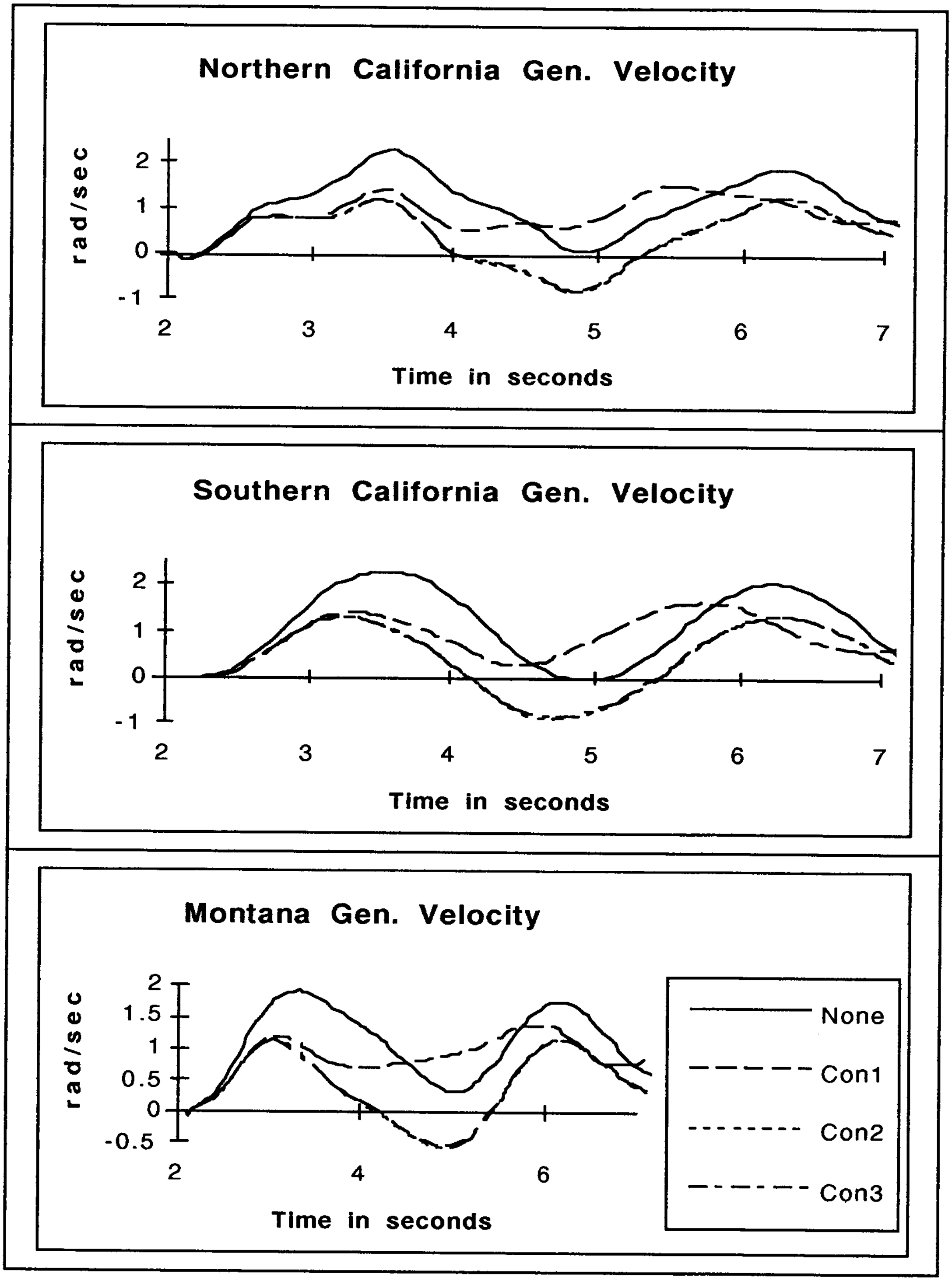

Figure E.7 Relative Generator Velocities for John Day-Chief Joseph Fault

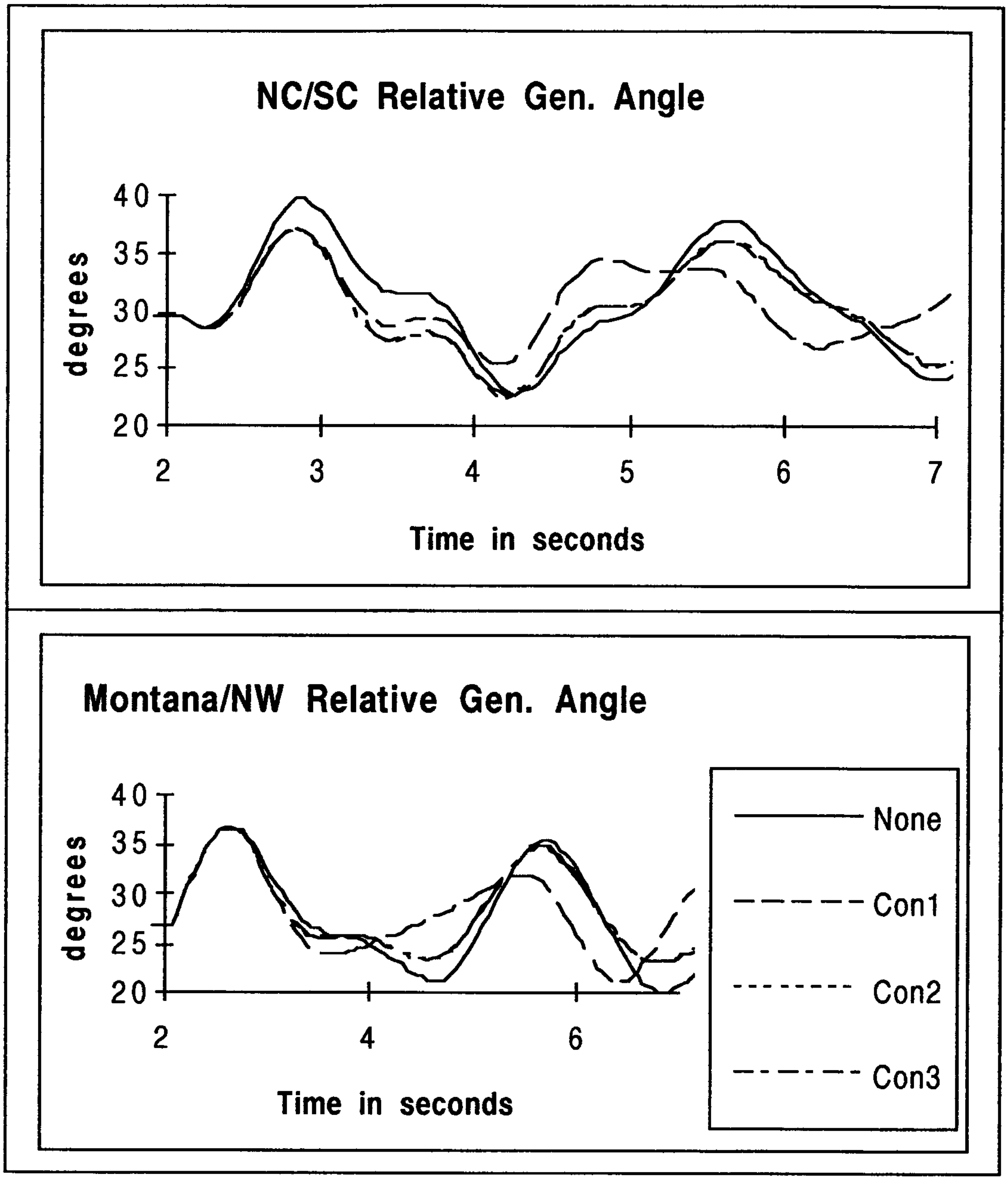

Figure E.8 Relative Generator Swing Angles for John Day-Chief Joseph Fault

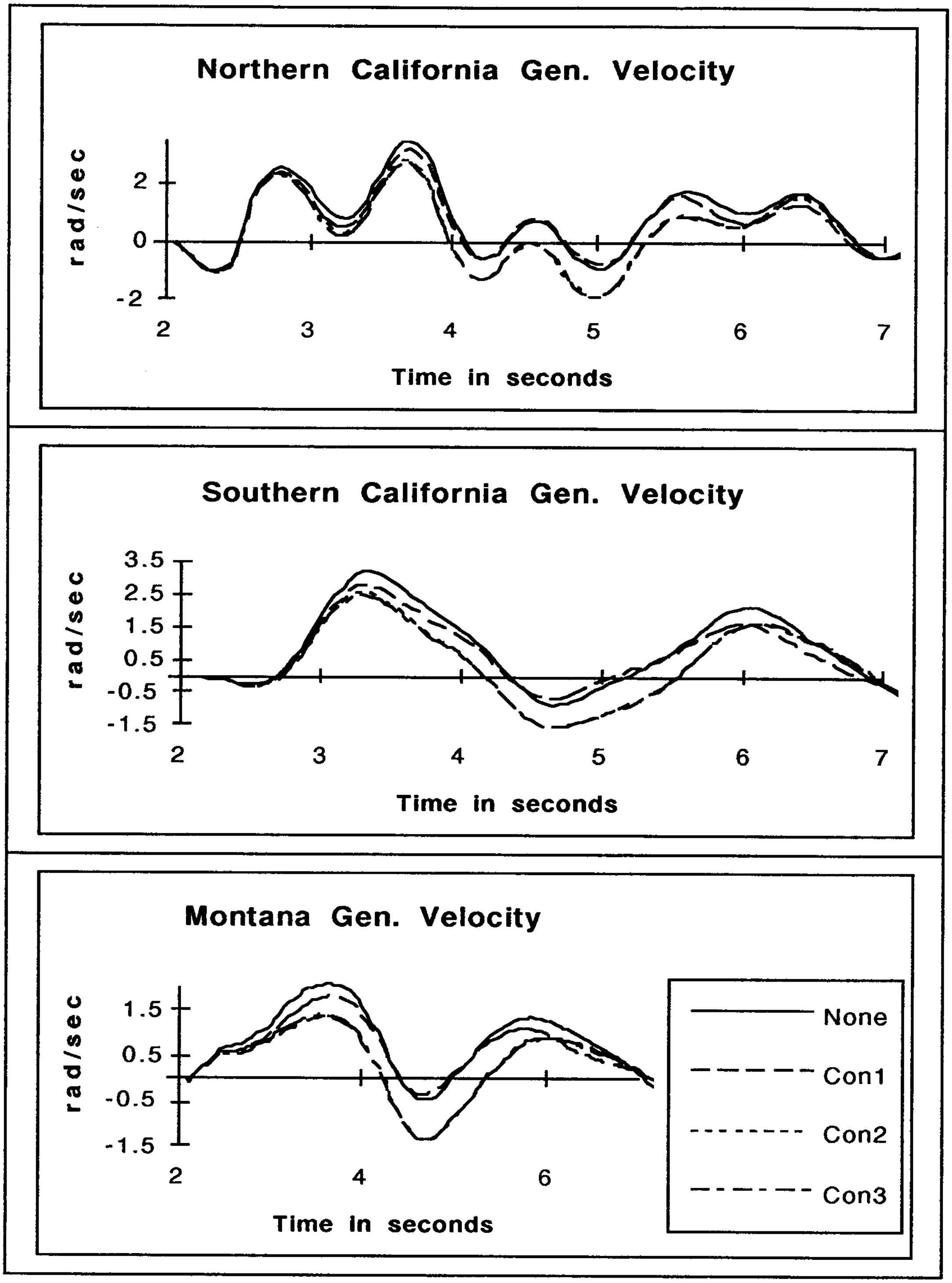

Figure E.9 Relative Generator Velocities for John Day-Northern California AC Intertie Fault

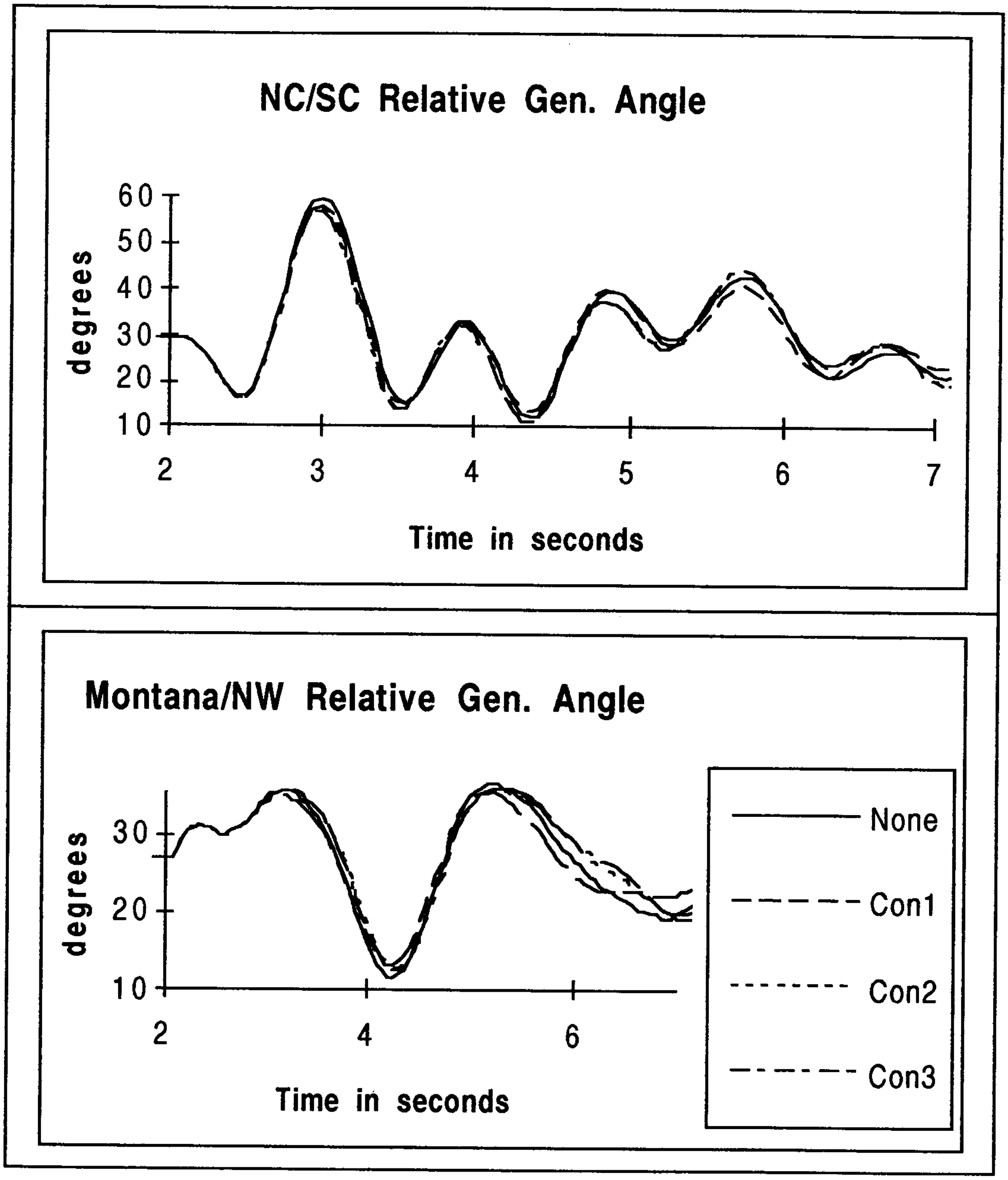

Figure E.10 Relative Generator Swing Angles for John Day-Northern California AC Intertie Fault

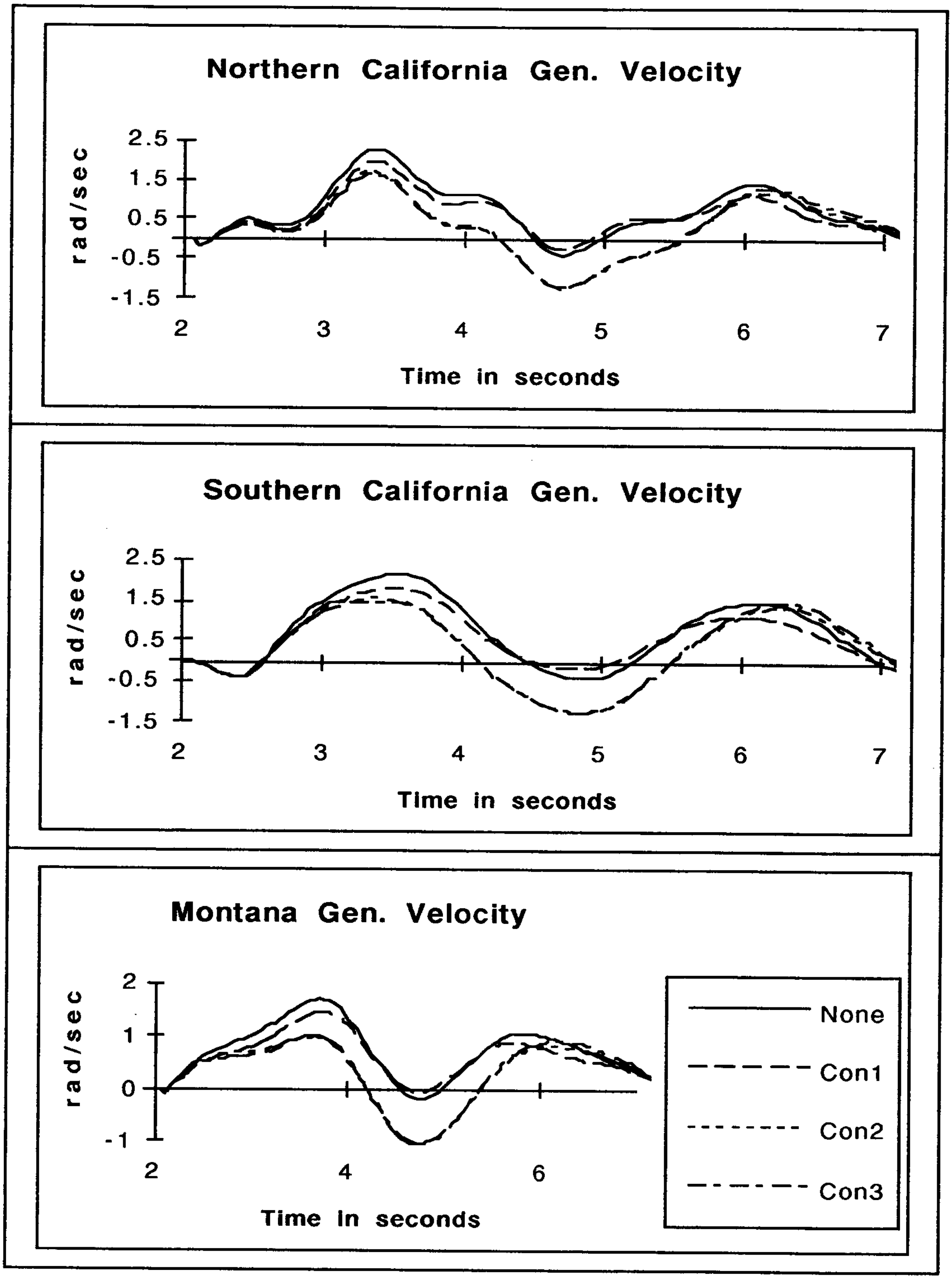

Figure E.11 Relative Generator Velocities for John Day-Southern California 3rd AC Intertie Fault

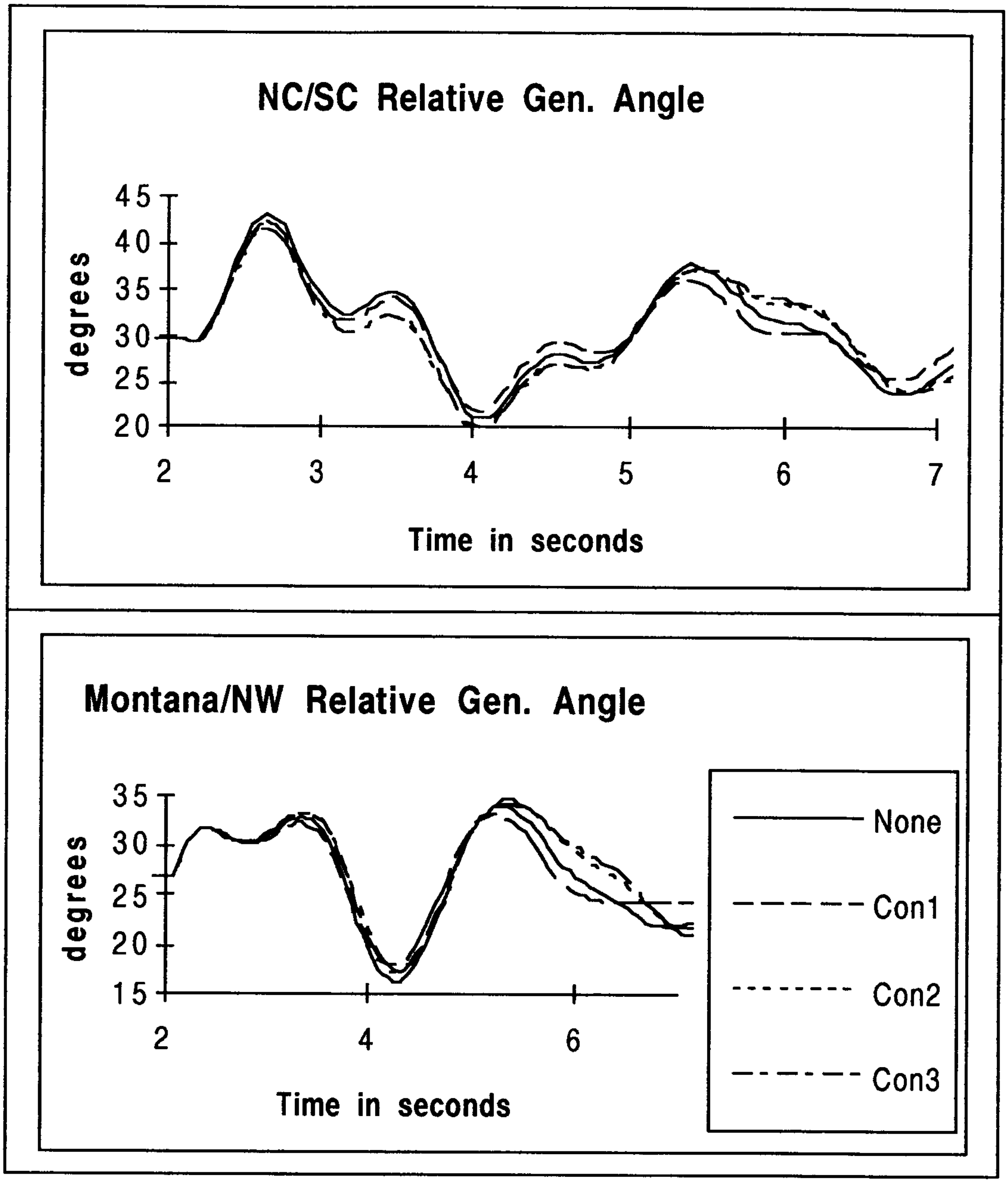

Figure E.12 Relative Generator Swing Angles for John Day-Southern California 3rd AC Intertie Fault

Thyristor Switched Braking

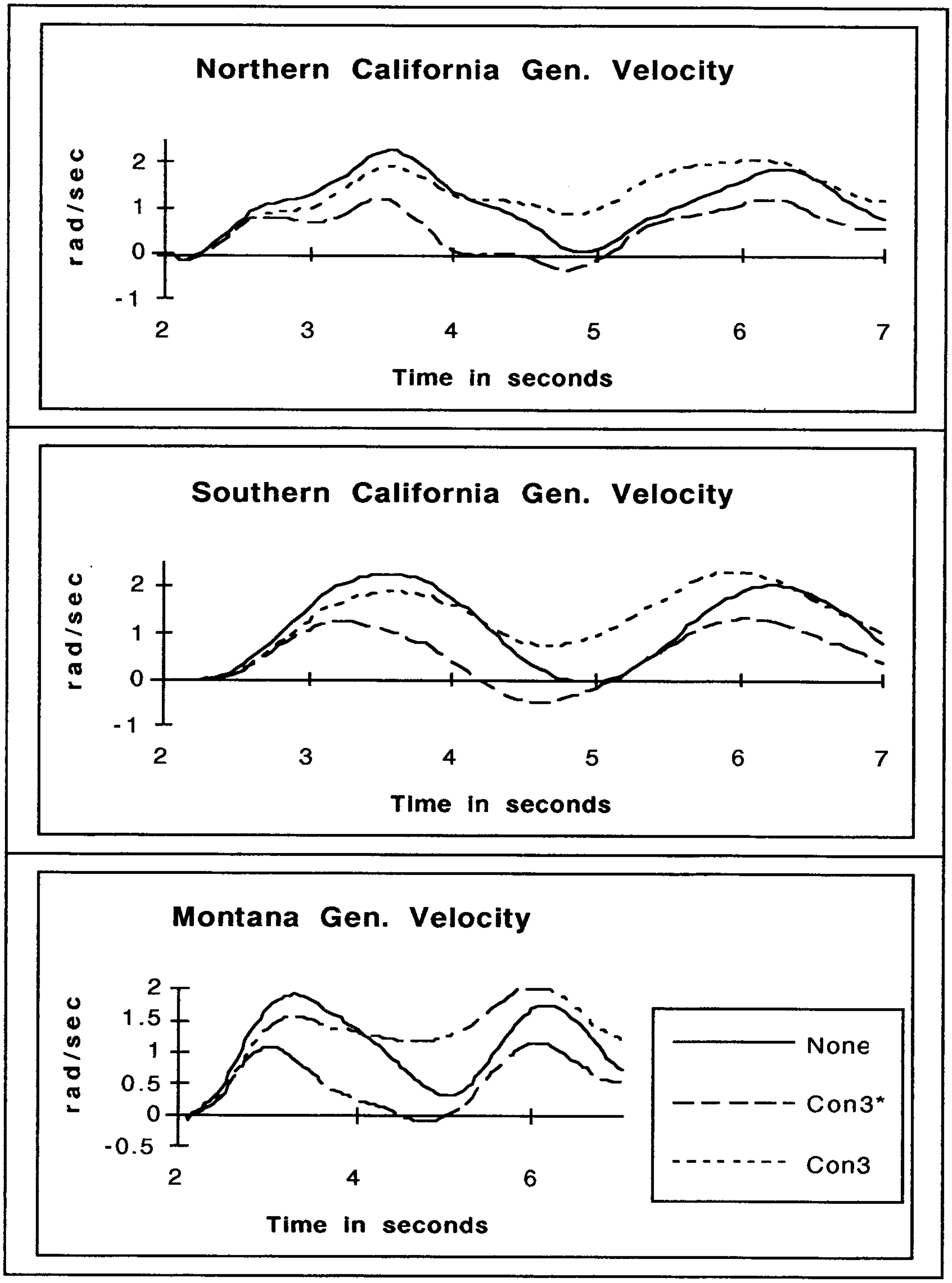

Figure E.13 Relative Generator Velocities for John Day-Chief Joseph Fault

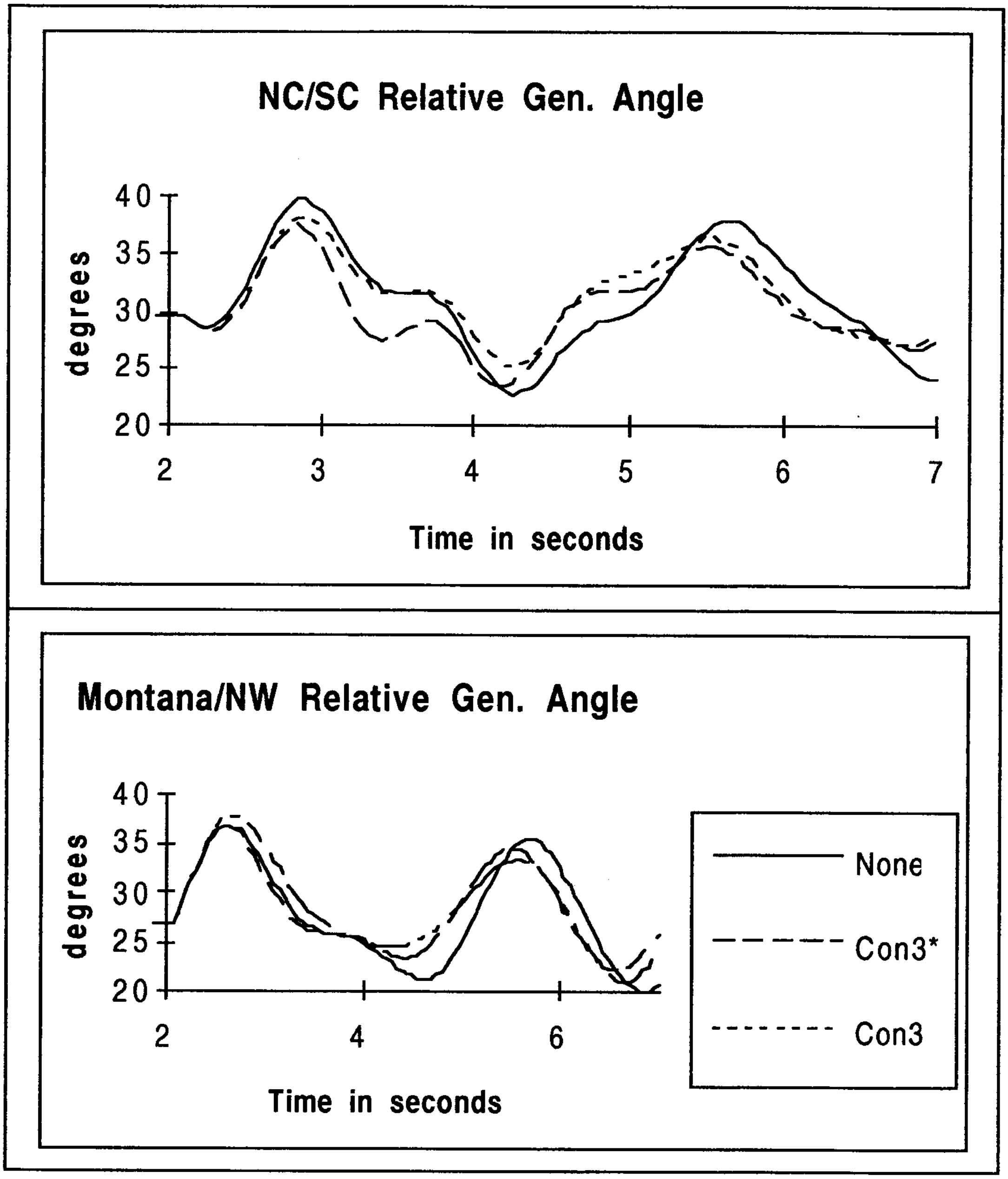

Figure E.14 Relative Generator Swing Angles for John Day-Chief Joseph Fault

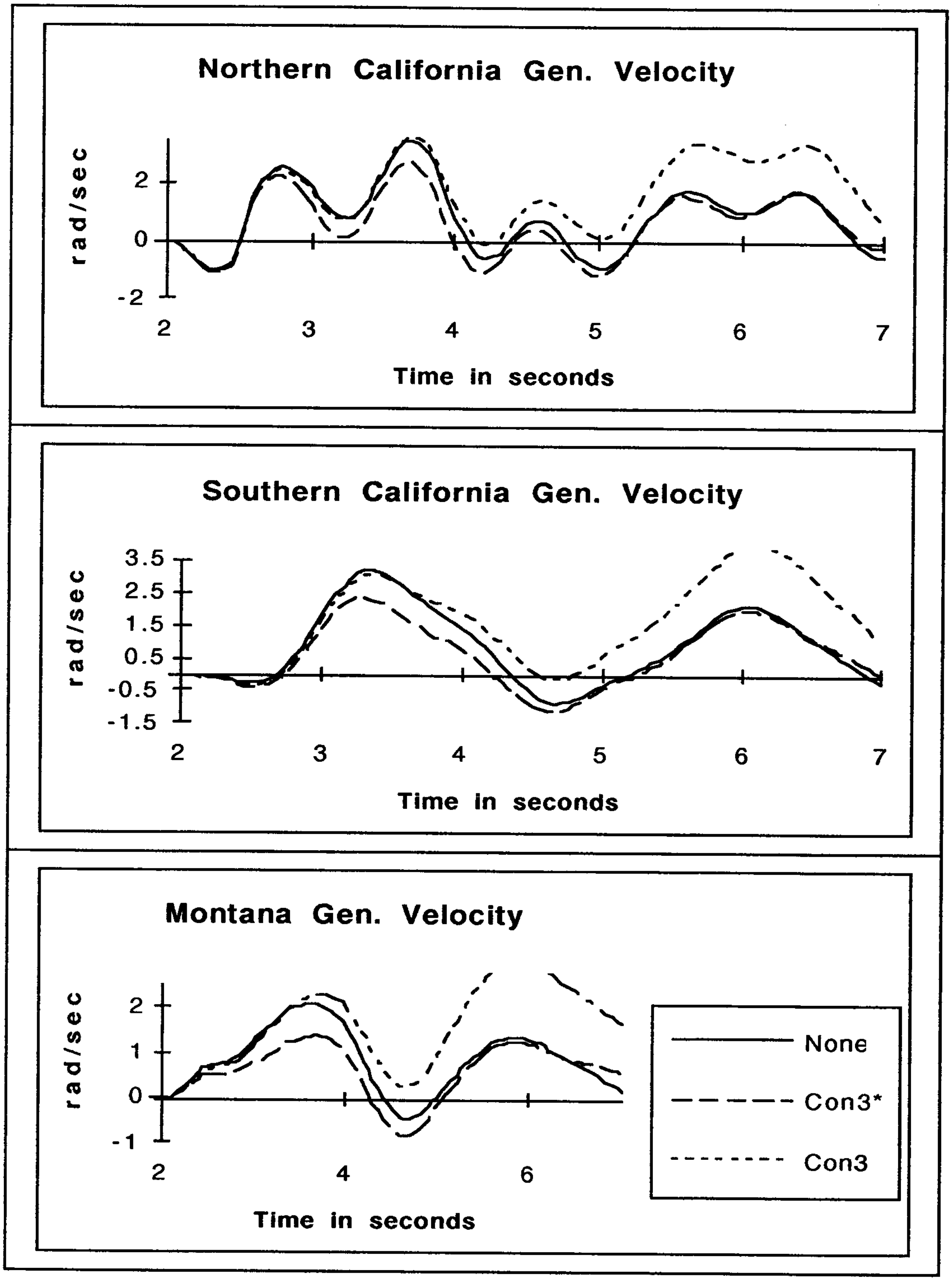

Figure E.15 Relative Generator Velocities for John Day-Northern California AC Intertie Fault

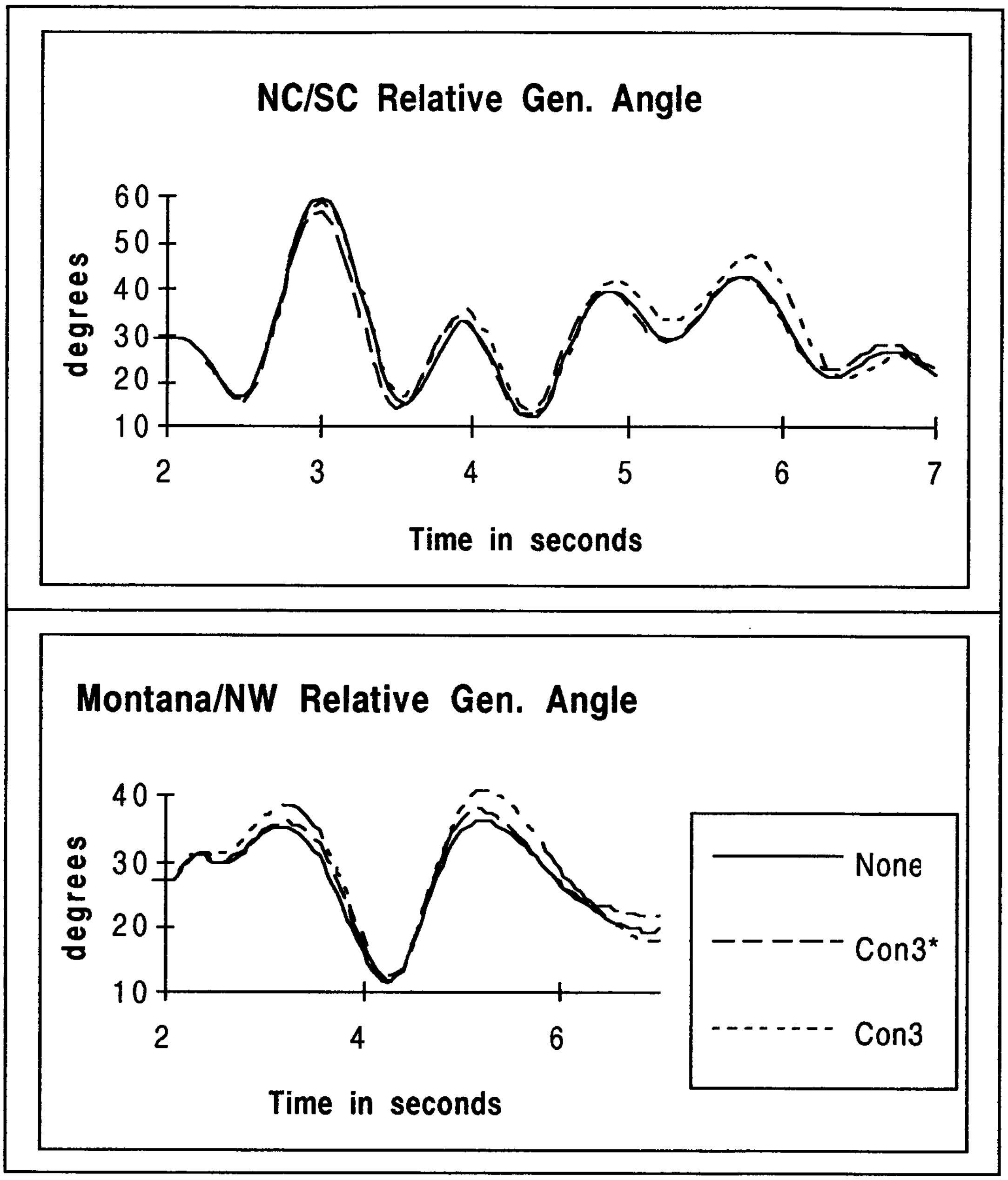

Figure E.16 Relative Generator Swing Angles for John Day-
Northern California AC Intertie Fault

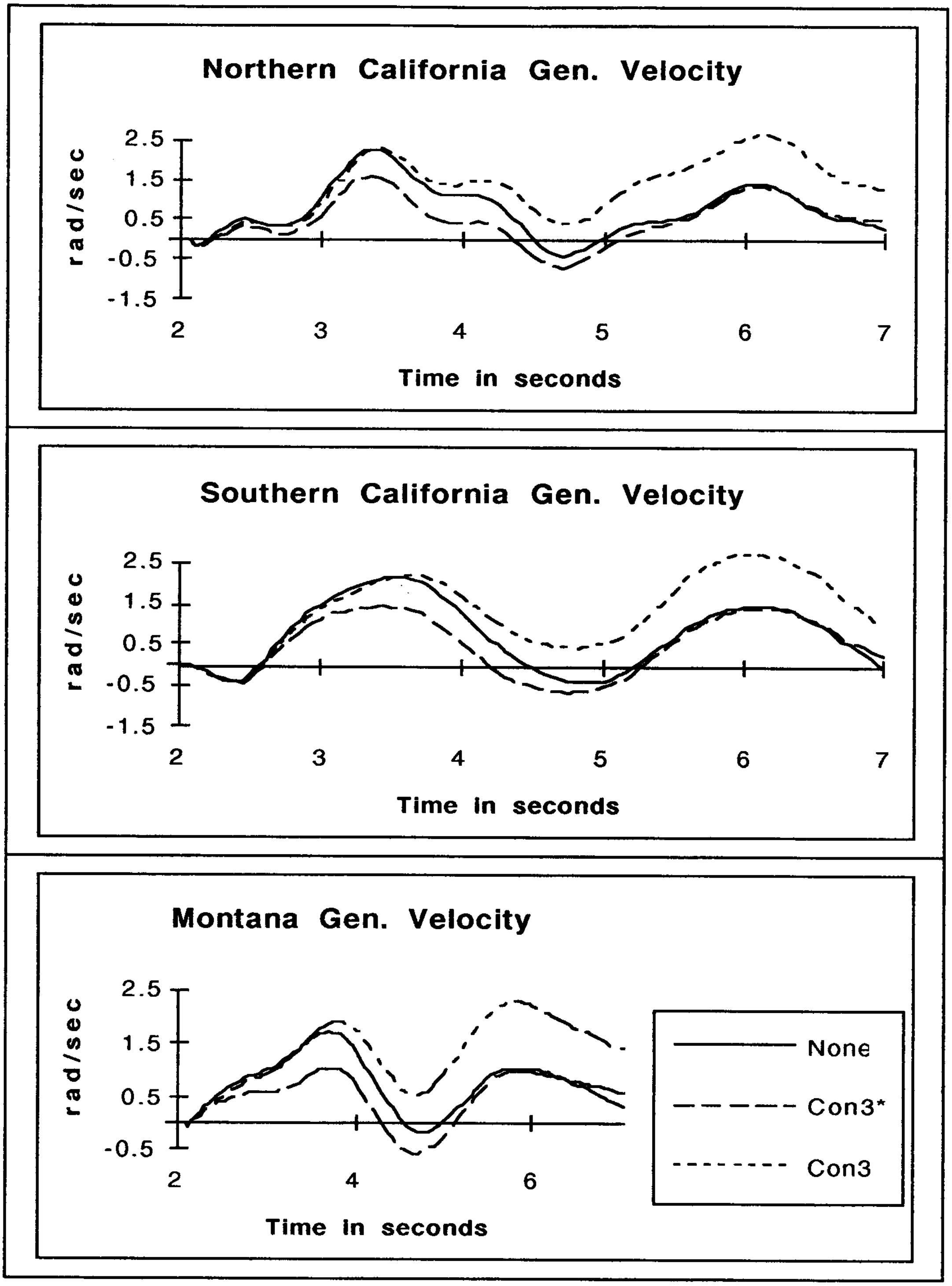

Figure E.17 Relative Generator Velocities for John Day-Southern California 3rd AC Intertie Fault

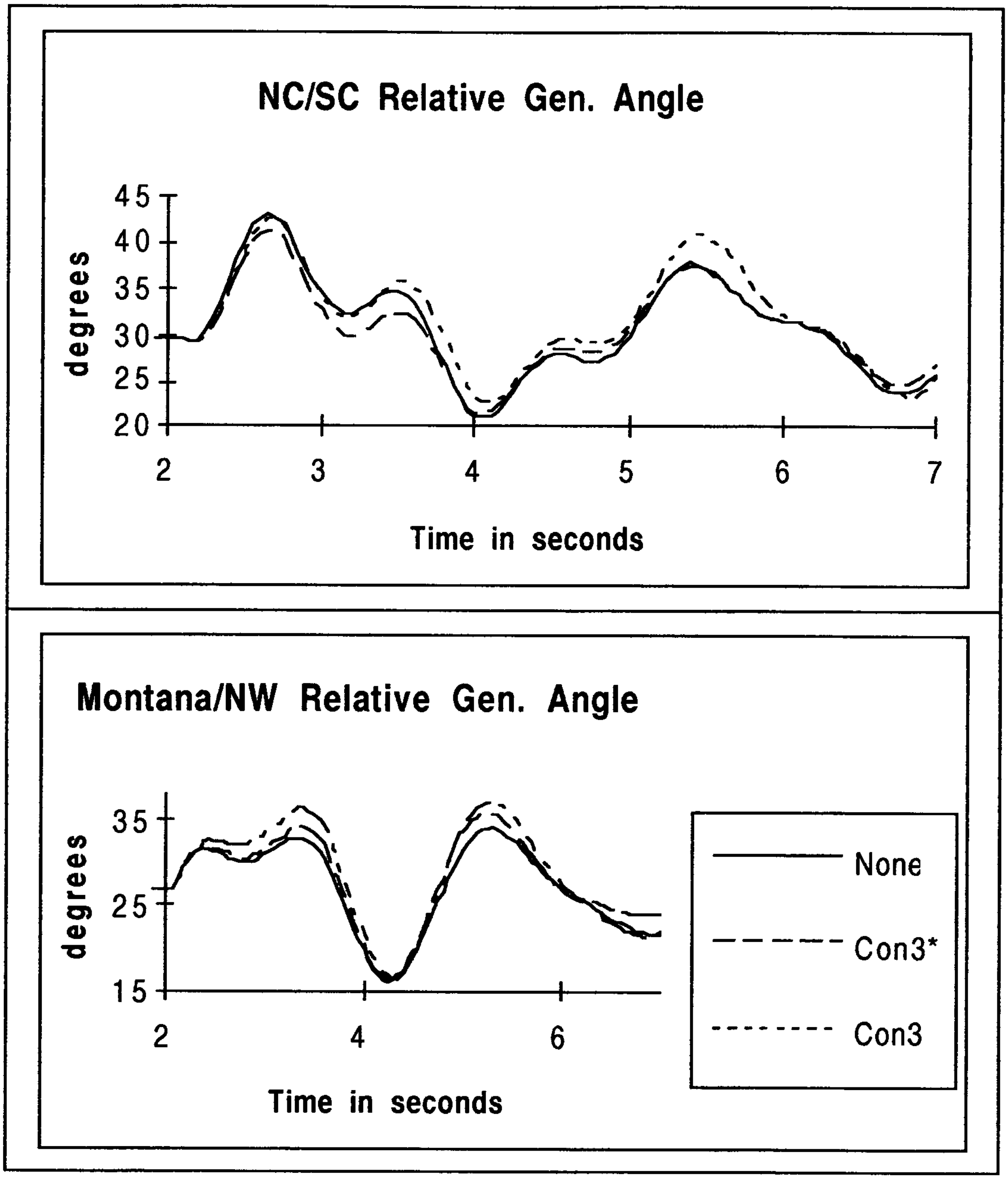

Figure E.18 Relative Generator Swing Angles for John Day-Southern California 3rd AC Intertie Fault

Appendix F Bonneville Power Administration 500 kV System Diagram

Figure F.1 BPA 500 kV Power System Diagram, 1994